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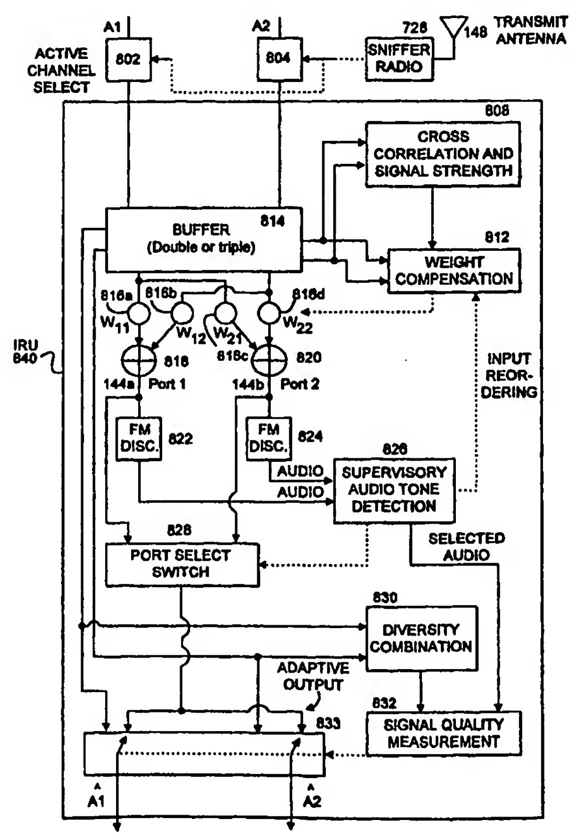
(54) Title: ADAPTIVE BEAMFORMING FOR WIRELESS COMMUNICATION

(57) Abstract

Method and circuitry for interference reduction in wireless communication (840); reducing interference from a source received in the same channel as a signal of interest (142); adaptive beamforming and scanning (154) so as to direct a sensitivity null (145) toward an interfering signal while still receiving the signal of interest; scanning wireless channels and applying adaptive beamforming to channels having interference. Selecting among signals based on a supervisory audio tone (826). Selecting a sample having a duration less than an inverse of a fade rate of the signal; determining a linear fit to a sample and transforming a signal based on minimization of variance from the linear fit.



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ADAPTIVE BEAMFORMING FOR WIRELESS COMMUNICATION

RELATED APPLICATION

This application claims the benefit of U.S. Provisional Application Serial No. 60/031,140, entitled *Adaptive Beamforming for Wireless Communication*, invented by Otis Frost, filed November 18, 1996, which is incorporated herein by reference.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The invention relates generally to wireless cellular communications systems, and more particularly to reduction of interference between signals sharing a common channel but emanating from different cells.

2. Description of the Related Art

In wireless cellular communications systems, interference between communication signals can reduce communication quality by introducing noise and static in the received signal and even causing dropped calls. Cellular systems typically are designed so that communication signals are used within prescribed geographically dispersed cells. Although multiple users may employ the same channel to communicate within different cells in the system, these cells ordinarily are sufficiently dispersed to limit interference between the signals. Nevertheless, as explained below, interference which degrades call quality sometimes occurs.

More specifically, a typical cellular system in a geographic area, such as a city, will have a prescribed number of channels allocated to it. This number, for example, may be a few hundred or more. In order to provide service to the maximum number of users, channels are reused. Figure 1 provides an

illustrative diagram of the cellular coverage pattern of a portion of an exemplary cellular system. The system is divided into a series of hexagonal cells, some of which are labeled here 102a-k. In order to prevent interference, the channels may be allocated so that the same channel is not reused in adjacent cells. For example, in Figure 1 all of the prescribed channels could be allocated throughout the cluster 106 of cells 102a-102g so that any given channel is used within no more than one cell of the cluster. In this exemplary system, the cluster 106 has seven cells, although clusters could be comprised of other numbers, patterns, or arrangements of cells. Cellular communication channels may be "reused," however, in a different cluster of cells outside the cluster 106. For example, cell 102k may use the same channels that are used in cell 102a. Cell layout geometry and frequency reuse are discussed in the book *Cellular Radio Systems* by Balston, et. al., eds., Artech House, Norwood MA, 1993.

Even though channels may not be "reused" within the same cluster, interference may still occur. For example, a transmission from a local user, which we shall refer to as the signal of interest, may be weak because that user is partially blocked behind a building, while a transmission from a user in a distant cell, which we shall refer to as an interfering signal, may be unusually strong because that user is driving in a car crossing over the top of a hill thus resulting in interference. Referring to Figure 1, assume for example, that base station 101a is attempting to receive a signal of interest from source 104a. The source, for example, may be a wireless telephone subscriber unit. Further assume that a channel used by signal of interest source 104a in cell 102a is also used by another interfering signal, source 104b, in cell 102k. In this illustrative situation, the signal from source 104b may interfere with the signal from source 104a and result in degradation of the signal from source 104a.

There are numerous other potential sources of interfering signals. For example, cellular transmissions in adjacent frequencies may leak into the channel transmitting the signal of interest, causing interference. This can happen, for instance, due to leakage of imperfect filters, particularly if the

adjacent channel signal is received much stronger than the signal of interest. Interference can also arise, for example, from intermodulation products from two or more strong signals passing simultaneously through a nonlinear element. The nonlinearity may be in the site signal processing chain or even outside the cell site, for example, in a rusty barbed-wire fence. Interference may also arise from non-cellular transmissions, intentional or unintentional, which find their way to the channel of the signal of interest.

Figure 2 is an illustrative diagram showing the distribution of representative components of an exemplary wireless cellular system throughout the various cells in the system. Each cell 102a-h has its own base station 101a-h for transmitting to and receiving from cellular users. The base stations 101 are connected to a wireless mobile telephone switching office (MTSO) 110. The MTSO 110 interconnects and manages the base stations 101a-h and provides a connection to the outside telephone network 112.

A typical base station has both transmit and receive antennas. A typical conventional base station employs directional antennas that divide the cell into three different 120 degree sectors 120a-c as shown in the illustrative drawings of Figure 3. A sector is typically served by three antennas, one transmit antenna 132 and two receive antennas 130a and 130b. Two receive antennas are provided in order to reduce the effect of Rayleigh fading. This configuration using two receive antennas is commonly known as a diversity antenna. In a system with diversity antennas, a signal can be improved by selecting the better signal from between the two receive antennas.

These techniques, however, are not particularly effective at reducing interference between signals at the same channel transmitted between users and base stations in different cells. It is therefore desirable to have a system that reduces the interference created by other cellular users or other signals sources transmitting on the same channel as a signal of interest.

In other applications such as radar, it is well known to employ multiple antennas together in a configuration known as phased array antennas. Such

phased array antennas may be comprised of tens or hundreds of antenna elements. When used as transmit antennas, such phased array antennas produce radiation patterns in which intensity may vary with beam direction. The portions of the beam pattern with higher intensity are commonly referred to as lobes, and portions of the beam with very low intensities are commonly referred to as nulls. By shifting the phase of the signals transmitted by the various antennas within the phased array antenna, the radiation pattern can be steered electronically so as to allow scanning. Similarly, when phased array antennas are used for reception, the sensitivity pattern can be steered dynamically by shifting the phase of the signals received by the different antenna elements in the array. In this manner, for example, a sensitivity main lobe and a sensitivity null can be steered. Depending on the number and configuration of elements in the phased array, the antenna may yield a complex pattern of higher and lower sensitivity regions, to null interferers and pass signals of interest.

Generally, as the number of antenna elements in a phased array antenna increases, the sensitivity of the antenna can be more effectively steered dynamically. For this reason phased array antennas often are constructed as a combination of many antenna elements.

It would be desirable to provide dynamic steering of the sensitivity of a cellular antenna in order to reduce interference from sources transmitting on the same channel as the signal of interest.

Unfortunately, installing phased array antennas in existing wireless communications systems presents numerous practical problems. For example, replacing antennas in a cellular system may require expensive materials and labor. Furthermore, environmental concerns and aesthetics may hinder the installation of new antennas. As cellular systems have become more common, so has citizen opposition to the construction of new antennas. Therefore, it would be advantageous to use existing cellular system antennas to reduce interference rather than replace them.

Antenna outputs may be filtered to isolate a channel of interest and then combined by using weights to produce a signal of interest. Treichler discovered a method of computing suitable weights to produce a signal of interest having a constant envelope or modulus. The method, called the Constant Modulus Algorithm (CMA), uses an iterative gradient-descent procedure to calculate the weights. Treichler and Agee demonstrated applications of CMA to separate frequency-modulated (FM) signals from interference. J.R. Treichler, B.G. Agee, "A New approach to Multipath Correction of Constant Modulus Signals." IEEE Transactions on Acoustics, Speech and Signal Processing, vol. ASSP-31, pp. 459-472, April 1983. This technology is applicable to interference reduction for analog cellular systems because FM signals are used by most analog cellular services worldwide. CMA produces a single signal, usually the strongest constant modulus (e.g. FM) signal in the channel if the algorithm is suitably initialized. However, the strongest signal in the channel is not the signal of interest if the interferer is received with stronger power. Modifications of CMA may be used to produce multiple candidate signals, from which the signal of interest may be identified.

Agee has published one method of computing multiple candidate constant-modulus signals, which may then be examined to select which is the desired signal of interest, regardless of which is strongest. Brian G. Agee, "Blind Separation and Capture of Communication Signals Using a Multitarget Constant Modulus Beamformer", 1989 IEEE Military Communications Conference. Agee's method is also attractive because it uses a compression-mapping method that can be based on a much shorter observation of data than a gradient-descent technique to arrive at a solution. Agee's method, also called Least Squares CMA (LS-CMA) and Multi-Target Modulus Restoral (MT-MORE), is optimized for the rapid tracking of multiple constant modulus signals in a non-fading environment. However, fading severely degrades the performance of equipment based on the above types of CMA.

Cellular signals are often received at their base stations with very significant fading, particularly in cities and particularly if they are transmitted from moving vehicles. Signals from cellular users may be received at their serving base station via multiple indirect paths (multipath) as opposed to direct line-of sight reception. This results in mutual interference between signal components on the multiple paths and causes amplitude variations on the total received signal at the cell site antennas. Furthermore, the cellular emitters may be in vehicles whose movement can cause Doppler shifts, resulting in Rayleigh fading on the total received signal envelope and random changes in the apparent angle-of-arrival of the signal, even without interference. The ability to reject interference effectively in a rapidly time-varying environment is important because some existing techniques such as CMA do not work well in a cellular environment. The envelope variations due to Rayleigh fading mask the envelope variations due to interference, greatly degrading CMA's ability to separate the desired signal from the interference.

Receiving antenna arrays are discussed above. For a system that attempts to provide an adaptive transmit antenna array that sends multiple signals from an antenna array through a propagation environment to several receivers, so that each receiver gets adequate desired signal with minimum crosstalk, see U.S. Patent No. 5,634,199, entitled *Method of Subspace Beamforming Using Adaptive Transmitting Antennas with Feedback*, by Gerlach et al., which is incorporated herein by reference. The Gerlach patent discusses the goal of using transmit beamforming guided by received supervisory audio tones (SATs).

SUMMARY OF THE INVENTION

The invention provides a new method for reduction of interference in a mobile communications system from a source received in the same channel as the signal of interest. The outputs of an array of two or more antennas are

combined so that the interfering signal is canceled while still receiving the signal of interest.

One aspect of the invention is a method of reducing interference on a channel in a mobile communication system having an array of at least two antennas including at least a first antenna and a second antenna. A first waveform is received on the channel on the first antenna and a second waveform is received on the channel on the second antenna. The first waveform and the second waveform are adaptively combined into a first candidate signal, and the first waveform and the second waveform are adaptively combined into a second candidate signal. The first candidate signal and the second candidate signal are selected among based on a supervisory audio tone.

Another aspect of the invention is the ability to reject interference in the rapidly time-varying environment of cellular signals, which can cause 100 Hz Rayleigh fading on a signal envelope. An aspect of the invention allows the desired signal to have a sloping envelope versus time, as might be caused by 100 Hz Rayleigh fading viewed over a time period that is short compared to the reciprocal fade rate (e.g. 3 ms.). Specifically, an aspect of the invention separates fading signals from interference by minimizing the deviation of the desired output signal's envelope from a sloped straight line versus time, instead of a constant, as CMA does. This allows the invention to separate envelope variations caused by the environment from faster envelope variations caused by interference and enables it to successfully reject interference in a Rayleigh-fading environment.

An embodiment of the invention provides a practical way to reduce interference in analog cellular communications by adding a digital signal processor at a cellular base station. The digital signal processor may be inserted easily into the normal cellular base station's signal distribution chain between the existing receive antennas and the station's radios by disconnecting and reconnecting a single coaxial cable per antenna. The processor can use the existing receiving antennas to form a phased-array, adaptive beamformer that

receives the signal from the intended cellular user while automatically canceling the interferer. The user's signal is identified as the signal having the correct supervisory audio tone (SAT) in its baseband. The user's radio-frequency signal is passed through the processor to the site radios with the interference removed or reduced. An advantage of the embodiment is that it requires no new antennas to be added to the base station, avoiding the expense and lengthy government approvals associated with adding new antennas which are usually necessary for a beamformer. Another advantage of the embodiment is that the new equipment requires no control communication with the existing cell site equipment, simplifying installation.

Another aspect of the present invention is the dynamic scanning of receive channels to provide interference reduction selectively to channels when they require interference reduction. If interference does not continuously occur on all channels, this aspect helps to reduce the cost of an implementation.

An embodiment of the invention includes a method of reducing interference in a mobile communication system having an array of at least two antennas by scanning channels used by the cell site to select one or more channels that may be improved by interference reduction, and then performing adaptive beamforming on those channels.

The scanning process, according to an aspect of the invention, uses a multistage rapid-qualification technique to minimize time between consecutive scans. Signal-to-interference-and-noise ratio (SINR) of a signal may be used as a rapid qualifier to determine if the signal is a good candidate for interference reduction before applying more complex tests.

An aspect of the invention is measuring instantaneous SINR on a signal by fitting a straight line to the envelope of the signal. According to an aspect of the invention, the SINR is determined by measuring the variance of the envelope from the straight line (caused by interference and noise) and the average envelope magnitude (which is related to the power of the strongest signal).

The adaptive beamforming combines the signals from the antennas in such a way as to produce more than one candidate signal for output. According to an aspect of the invention, the candidate signals are produced by repeatedly:

determining a block correlation estimate from a short sample of the antenna outputs, the sample being taken over a time period that is short compared to the reciprocal fade rate of the signal,

determining a complex-limited signal scaled by a linear fit to its envelope, taken over the same time period,

updating a set of weights based on the block correlation estimate and the complex-limited and scaled signal,

determining a set of m array output signals based on the updated weights operating on the antenna outputs using the first of the m array output signals as the first candidate output signal,

determining weights that generate a second signal that is hard-orthogonal to the first candidate output signal, and which minimizes the distance to the second array output signal. Similarly, determine weights that generate third, fourth and mth hard-orthogonal signals that are orthogonal to all the previous hard-orthogonal signals and minimize distance to their respective array output signals,

determining a softening parameter,

determining soft-orthogonalized second, and third through mth signals based on the hard-orthogonalization and the softening parameter, forming the second, third, through mth candidate signals,

continuing the process by iterating the above steps to refine the candidate signals and provide better estimates of the signal of interest. On the last step in the iteration the softening is not done, in order to produce the best signal estimates.

The above procedure, according to an aspect of the invention, produces a set of candidate output signals based on new weight estimates. According to another aspect of the invention, the weights from the previous time epoch (termed the "old weights") are used to produce additional candidate signal estimates. Another candidate signal estimate is produced by the same type of diversity combiner used by the cell site equipment to use as a baseline comparison. The candidate signal selected for output, according to an aspect of the invention, is usually the signal with the highest SINR and the correct supervisory audio tone (SAT) that is known to be used by the proper user of the cell site at the selected channel. According to another aspect of the invention, the selection process uses selection logic to cope with unusual situations, such as no candidate signal having a SAT.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is an illustrative drawing of an exemplary pattern of cells including a cluster of cells in a conventional wireless cellular system;

Figure 2 is an illustrative drawing of the cluster of cells of Figure 1 showing several conventional components of a wireless cellular system disposed within cells of the cluster;

Figure 3 is a generalized illustrative drawing of a cell and its constituent sectors;

Figure 4 is an illustrative drawing of a conventional cellular antenna;

Figure 5 is a simplified illustrative block diagram of an adaptive beamforming and scanning processor showing an exemplary pattern of lobes and nulls in accordance with an embodiment of the invention;

Figure 6 is a more detailed illustrative block diagram of an adaptive beamforming and scanning processor integrated with conventional base station equipment in accordance with an embodiment of the invention;

Figure 7 is a more detailed illustrative block diagram of the adaptive beamforming and scanning processor of Figure 5;

Figure 8 is an illustrative block diagram of an interference reduction unit;

Figure 9a is an illustrative diagram of a conventional cellular frequency band, and Figure 9b is the cellular frequency band of figure 9a with a single cellular channel notched out;

Figure 10 is an illustrative flow chart of a "set-on" method of interference reduction in accordance with an embodiment of the invention;

Figure 11 is an illustrative flow chart of a first tier of tests for the "set-on" method of Figure 10;

Figure 12a-12b is an illustrative flow chart of a second tier of tests for the set-on method of Figure 10;

Figure 13 is an illustrative flow chart of a method of determining if a signal of interest is present in accordance with an embodiment of the invention;

Figure 14 is an illustrative flow chart of a method of applying adaptive beamforming to a channel in a wireless cellular communication system in accordance with an embodiment of the invention;

Figures 15 a and b are an illustrative flow chart of a method of applying adaptive beamforming to a channel in a wireless cellular communication system using linear fit according to an embodiment of the invention;

Figure 16 is an illustrative diagram of a signal including a portion used for a data sample.

DETAILED DESCRIPTION

The present invention comprises a novel method and apparatus for reducing signal interference in a cellular wireless communication system. The following description is presented to enable any person skilled in the art to make and use the invention. Descriptions of specific applications are provided only as examples. Various modifications to the embodiments described will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the invention. Thus, the present invention is not intended to be limited to the embodiments shown.

The following paper is hereby expressly incorporated by reference: "Blind Separation and Capture of Communication Signals Using a Multitarget Constant Modulus Beamformer" by Brian G. Agee, 1989 IEEE Military Communications Conference [hereinafter, "Agee paper"].

Figure 5 is a generalized block diagram of an adaptive beamforming and scanning processor 154 in accordance with an embodiment of the invention. The adaptive beamforming and scanning processor 154 operating with two antennas directs a sensitivity null 140 toward an interferer 144.

In operation, the adaptive beamforming and scanning processor 154 initially will not have identified which signal is an interferer and which is a signal of interest. The beamforming and scanning processor 154, therefore, attempts to isolate the signals from each other and to then identify the signal of interest. Thus, beamforming and scanning processor 154 adaptively combines waveforms from the antennas to yield candidate signals. Adaptively combining waveforms means that the waveforms are combined adaptively to the environment rather than being combined in a fixed combination. In a fixed combination configuration, waveforms from antennas are combined in a way that does not vary over time.

More particularly, the adaptive beamforming and scanning processor 154 attempts to isolate the strongest and next strongest received signals. The processor 154 outputs the strongest signal to a first port 144a by steering a sensitivity null towards the next strongest signal and outputs the next strongest signal to a second port 144b by steering a sensitivity null in the direction of the strongest signal. Based on information contained within the signals, the adaptive beamforming and scanning processor 154 attempts to identify the signal of interest from among the signals on ports 144a and 144b.

In the present embodiment the adaptive beamforming and scanning processor continuously updates its beam pattern and selects the correct port so as to direct a null 140 at the interferer 144. For example, the interferer source 144 or the signal of interest source 146 may move requiring alteration of the beam pattern. This process of interference reduction is referred to herein as adaptive beamforming.

The illustrative drawings of Figure 6 show an adaptive beamforming and scanning processor 154 integrated with conventional base station equipment in accordance with an embodiment of the invention. The signals from the antennas 146a and 146b are provided to filters and pre-amps 150. The signal from the filters and pre-amps 150 are provided to the first splitter 152. The signals from the first splitter are provided to the adaptive beamforming and scanning processor 154, and to the remaining site and distribution network 156. The signal from the remaining site and distribution network 156 is provided to the base station receivers 158. The base station receivers 158 are coupled to the base station controller 162, the MTSO interface 160, and the base station transmitters 164. The base station controller 162 is coupled to the Mobile Telephone Switching Office (MTSO) interface 160. The MTSO interface 160 is coupled to the base station transmitter 164. The MTSO interface 160 is linked to the MTSO 110 and to the base station transmitters 164. The base station transmitters 164 are also coupled to the existing transmit antenna 148 and to the adaptive beamforming processor 154. The base station transmitters 164 are

coupled to the adaptive beamforming and scanning processor 154 in order to allow the adaptive beamforming and scanning processor 154 to "sniff" the transmitted signal in order to ascertain the corresponding receive frequencies as explained more fully below.

In operation, radio frequency signals are received on antennas 146a-b and are provided to filters and preamps 150. It will be appreciated that the base station transmits and receives on a plurality of cellular communications channels. There may be interference on any of these channels. Thus, at any given time, the receive antennas 146a and 146b may be simultaneously receiving numerous different signals of interest on different channels. Moreover, at any given time, some of these signals of interest may experience interference and others may not. The role of the processor is to improve the quality of signals of interest that experience interference by reducing the interference. The adaptive beamforming and scanning processor 154 evaluates signals operational on the selected channels to determine whether to apply interference reduction to such signals. The selected channels are channels in the channel plan of the base station and are such that the transmitter on the corresponding transmitting frequencies is deemed to be active. If the adaptive beamforming and scanning processor 154 determines that it will apply interference reduction to signals on the selected channel, then it applies adaptive beamforming to the signals, and provides the signal, which has been processed to reduce interference, to the remaining site distribution network 156. If the adaptive beamforming and scanning processor 154 determines that it will not apply interference reduction to the radio frequency signal, then it provides the original (unprocessed) radio frequency signal to the remaining site distribution network 156.

A channel represents a subset of the communication medium that is used for communication between at least two entities. The channel may comprise a frequency or other subset of the communication medium such as a band of

frequencies centered about a frequency or a set of frequencies used in a frequency hopping scheme.

Figure 7 shows an illustrative block diagram of the adaptive beamforming and scanning processor circuit 154. This circuit 154 selects respective channels used for reception by the cellular system base station and, for each selected channel, evaluates whether a signal of interest (SOI) on such selected channel is interfered with by another signal operative on the same channel. Upon identifying such interference, the adaptive beamforming and scanning processor 154 attempts to reduce the interference. The embodiment shown in Figure 7 is operative with Lucent base station equipment, but the invention could be implemented in conjunction with other OEM equipment as an alternative.

Since a base station typically services three sectors, it will have a set of three "right" receive antennas 146a, a set of three "left" antennas 146b, and a set of three transmit antennas 148. In Figure 7 each set of three antennas is represented by a drawing of one antenna.

Radio frequency signals from "left" antennas 146a and "right" antennas 146b are provided to filters 701 and 731 respectively which filter out cellular signals in a 22.5 MHz bandwidth or less at approximately 900 MHz. The signals from the filters 701 and 731 are provided to low noise amplifiers (LNA) 702 and 732 respectively. The signals from the LNA's 702 and 732 are provided to splitters 754 and 756 respectively. The signals from splitters 754 and 756 are normally provided to block down converters 703 and 717 respectively, which provide down converted signals centered approximately at 65 MHz having a bandwidth of 22.5 MHz. The embodiment shown is built for analog cellular (AMPS). For this reason, the signals from splitters 754 and 756 are also provided to the site distribution in order to allow other cellular signals (e.g., CDMA and CDPD) to pass. The signals from the block downconverters 703 and 717 are provided to analog to digital converters 704 and 718 respectively for band pass sampling at 52 Megasamples per second. The output

of the analog to digital converters 704 and 718 are digital versions of the baseband. These signals are provided to six channel downconverters 705 and 719. Although six channel downconverters 705 are represented here, a larger number could be used. The output of the six channel downconverters 705 and 719 respectively are provided to the adaptive beamforming and scanning module 706.

For each of the three right antennas 146a, there is a separate corresponding block downconverter 703 and a separate corresponding analog to digital converter 704. Similarly, for each of the three left antennas 146b, there is a separate corresponding block downconverter 717 and a separate corresponding analog to digital converter 718. The channel downconverters 705 select channels from the left antennas 146a. The channel downconverters 719 select channels from the right antennas 146b. Thus, the block downconverters 703 are each coupled to a left antenna 146a in one sector, while the channel downconverters 705 can select channels from the left antennas 146a in any sector. Similarly, the block downconverters 717 are each coupled to right antennas 146b in one sector, while the channel downconverters 719 can select channels from the right antennas 146b in any sector.

The six channel down converters 705 and 719 are responsive to the control 730 which controls which six channels are selected from the total collection of receive channels handled by the base station. The adaptive beamforming and scanning module 706 has a total of six interference reduction units 840. An interference reduction unit 840 looks at a channel to determine whether to apply interference reduction to that channel. If the interference reduction unit 840 determines that interference reduction should not be applied, then the channel downconverters 705 and 719 select another channel for evaluation. In this manner, a large number of channels can be scanned for the need for interference reduction, although only channels having actual interfering signals will be subjected to the interference reduction.

In order to reduce interference on a channel, the adaptive beamforming and scanning processor 154 removes ("notches") the channel from the baseband signal so that the channel can be replaced with a version of the channel without interference. Figures 9a and 9b are illustrative drawings of the notching of a signal. For example, signal 902 has a selected channel notched that was present in signal 900. The adaptive beamforming and scanning module attempts to notch a channel from a baseband signal and add back to the baseband a signal that has been cleaned up through interference reduction, while leaving the other channels unchanged.

The selected channel is notched by subtracting the channel from the baseband. Subtractors 707 and 720 receive the selected channel from channel downconverters 705 and 719 respectively and provide the inverse of the selected channel to channel upconverters 708 and 721 respectively. After channel upconverters 708 and 721, the inverted signals then are added to the baseband in adders 709 and 722. In this manner, the selected channel is effectively subtracted ("notched") from the baseband. The baseband is provided from the analog to digital converters 704 and 718 through delay circuits 723 and 724. The delay circuits are employed because the signal from the channel upconverters 708 and 721 is delayed relative to the output of the analog to digital converters 704 and 718. The delay provided by delay circuits 723 and 724 is selected to help match the delay that occurs in the channel downconverters 705 and 719 and channel upconverters 708 and 721. The delay is set to a value between 0 ms and 2 ms.

The outputs of the channel downconverters 705 and 719 are provided to the input of the adaptive beamforming and scanning module 706. The adaptive beamforming and scanning module attempts to perform interference reduction on the selected channels and provide the cleaned signals to the inputs of subtractors 707 and 720. From the subtractors 707 and 720, the signal travels through the channel upconverters 708 and 721 respectively. From the channel

upconverters 708 and 721, the signal travels to the adders 709 and 721, where it replaces the channel that was notched.

The outputs of adders 709 and 722 are coupled to digital to analog converters 710 and 725 respectively. The outputs of digital to analog converters 710 and 725 are coupled to block converters 711 and 726 respectively. Block converters 711 and 726 are coupled to amplifiers 746 and 726 respectively. Amplifiers 744 and 746 are provided with a dual 24 V dc power supply 752 for high reliability. The amplifiers 744 and 746 are employed to make up for loss from the relays 740 and 742 and splitters 748 and 750.

Amplifiers 744 and 746 are coupled to splitters 748 and 750 respectively. Splitters 748 and 750 are coupled to RCF distribution 712. RCF distribution 712 is coupled to cell radios 713. Cell radios 713 are coupled to combiners and power amp 714. Combiners and power amp 714 are coupled to coupler 716. Coupler 716 is coupled to splitter 760 and to transmit antennas 148. Splitter 760 is coupled to switch 727 in order to provide transmit signals to the sniffer radio 728. Sniffer radio 728 is coupled to switch 727, which selects one of the three antennas and provides the signal from the selected antenna to the sniffer radio 728. The sniffer radio 728 is used for sniffing the transmitted signals in order to determine the receive frequencies used by the base station. The sniffer radio 728 is used because the adaptive beamforming and scanning processor does not otherwise have access to the list of frequencies used by the base station. In an alternative embodiment, the adaptive beamforming and scanning processor is provided the receive frequencies directly from the base station equipment in an manner other than by observing the transmit antennas.

Relay 740 provides the following states. In the first state, relay 740 connect the output of pre-amp 702 to the inputs of block downconverters 703 and connects the output of block upconverters 711 to the input of RCF distribution 712. In the second state, relay 740 connects the output of pre-amp 702 to the input of RCF distribution 712 and breaks the connection of output of

pre-amp 702 to the input of block downconverters 703 and the output of block upconverters 711 to the input of RCF distribution. In the first state, the relay 740 allows adaptive beamforming to occur on the signals from the pre-amp 702. In the second state, the relay 740 causes the adaptive beamforming circuitry to be bypassed.

Relay 742 is connected in a similar manner. In the first state, relay 742 connect the output of pre-amp 732 to the inputs of block downconverters 717 and connects the output of block upconverters 726 to the input of RCF distribution 712. In the second state, relay 742 connects the output of pre-amp 732 to the input of RCF distribution 712 and breaks the connection of output of pre-amp 732 to the input of block downconverters 717 and the output of block upconverters 726 to the input of RCF distribution 712. In the first state, the relay 742 allows adaptive beamforming to occur on the signals from the pre-amp 732. In the second state, the relays cause the adaptive beamforming circuitry to be bypassed.

Referring to Figure 8, there is shown an illustrative diagram of an interference reduction unit circuit 840 coupled to other circuitry in the cellular base station. In one embodiment, the interference reduction unit circuit is actually implemented as a programmed microcomputer. The interference reduction unit could also be implemented in the form of an application specific integrated circuit.

The interference reduction unit 840 helps to reduce interference in a cellular system by employing adaptive beamforming. In Figure 8 the interference reduction unit 840 is shown in a system which employs only two receive antenna elements 146a and 146b. It will be understood that the interference reduction 840 unit can be structured to service other numbers of antenna elements (for example, 3, 4, 5, 6, or more antenna elements). If the interference reduction unit were changed to service a larger number of antennas, the number of ports could change while still remaining in the spirit of the invention.

Sniffer radio 728 is coupled to transmit antenna 148 and to channel selection logic 802. Receive antennas 146a and 146b are coupled to the inputs A1 and A2 through downconverters shown in Figure 7. Channel selection logic 802 and 804 controls the channels provided to inputs A1 and A2 respectively. Buffer 814 is a double or triple buffer, allowing for sampling of new data while old data is being processed. Computations are performed on the buffered signals before they are potentially modified by beamforming and output. Antenna cross-correlation and signal strength measurements are made from the buffered data 814 and coupled to weight computation circuitry 812. Weight computation circuitry 812 yields complex weights that scale and phase shift the signals. Buffer 814 couples the signals to weights 816a-816d. Weights 816a and 816b are coupled to adder 818, and adder 818 provides output to port 1, 144a. Weights 816c and 816d are coupled to adder 820, and adder 820 provides output to port 2, 144b.

Port 144a is coupled to the FM discriminator 822 and the port select switch 828. Port 144b is coupled to the FM discriminator 824 and the port select switch 828. FM discriminators 822 and 824 are coupled to supervisory audio tone detection circuitry 826. Supervisory audio tone detection circuitry 826 determines which port contains interference. This circuitry is coupled to port select switch 828 and signal quality measurement circuitry 832, which determines whether the adaptive beamformed output is better than the diversity combiner output. Diversity combiners are described in Lee, William C.Y., Mobile Communications Design Fundamentals, second edition, 1993, Wiley, New York, pp. 119-125, which is incorporated herein by reference. Port select switch 828 and signal quality circuitry 832 are coupled to switch 833, which outputs the "best" signal.

The channel plan is the collection of channels used by a base station. The sniffer radio 728 helps to determine the base station channel plan. By observing frequencies used for transmission on the transmit antenna. Then the

receive frequencies are determined by adding or subtracting an offset of 45 MHz to or from each of the transmit frequencies detected.

The interference reduction unit 840 operates in two modes, "set-on" and "copy". In the "set-on" mode, channels are evaluated to determine whether to apply adaptive beamforming interference reduction. If the interference reduction unit 840 determines that it will apply adaptive beamforming interference reduction to the channel, it then enters the "copy" mode and applies adaptive beamforming interference reduction to the channel.

The sniffer radio 728 is also used to determine whether a channel is currently not in use, even if it is in the base station channel plan. If the channel is currently not in use, another channel in the base station channel plan is selected.

In set-on mode, signal-to-interference-and-noise (SINR) and signal power measurements are made. SINR is measured in order to determine whether at least two different signals are present, the two signals' relative (to each other) amplitudes and the signals' magnitude above the noise floor. If only one signal is present, or if the signals are not close enough to each other in amplitude, or if the signals' magnitude is sufficiently above the noise as determined by the SINR as well as the power measurement, the circuitry 808 causes the interference reduction unit 840 to select another channel.

Weight computation circuitry 812 calculates weights from the input signals in buffer 814 using the least squares minimization, as discussed below. For more discussion of least squares minimization, refer to the paper "Blind Separation and Capture of Communication Signals Using a Multitarget Constant Modulus Beamformer" by Brian G. Agee, 1989 IEEE Military Communications Conference, which is fully incorporated herein by reference. The Agee paper describes a multi target least squares constant modulus MT-LSCMA algorithm. The weights are provided to weight adders 816a-816d. By providing different sets of weights to the different pairs of weight adders, different signals may be output to the different ports 144a and 144b. It is

appreciated that algorithms other than least squares minimization could be used to calculate weights that can be applied in order to separate signals and output different signals to different ports. In this embodiment, weight computation circuitry 812 is used in copy mode to calculate weights used for adaptive beamforming.

FM discriminators 822 and 824 provide baseband signals to supervisory audio tone detection circuitry 826. The supervisory audio tone detection circuitry 826 analyzes the output of the FM discriminators 822 and 824 to determine whether the same supervisory audio tone (SAT) is present on both ports during set-on mode. If the same SAT is present on both ports, then the supervisory audio tone detection circuitry 826 causes the interference reduction unit 840 to select a different channel. The supervisory audio tone detection circuitry 826 also analyzes the output of the FM discriminators 822 and 824 to determine which port contains the signal of interest in set-on and copy mode. The signal of interest on a port is identified as the signal having a SAT equal to the one expected of the signal of interest. The supervisory audio tone detection circuitry 826 causes the port select switch 828 to select the port containing the signal of interest in the set-on mode and in the copy mode.

It is appreciated that methods other than ones using the detection of SATs could be used to identify a signal of interest. For example in a digital cellular system, where signals are identified by a signature bit or combination of bits, this bit or collection of bits could be used to identify a signal of interest without departing from the spirit of the invention.

The diversity combination circuitry 830 performs an operation called diversity combination in set-on mode and in copy mode. The diversity combination circuitry 830 is implemented in functionally the same way the manufacturer of the base station equipment implements it. Each of several base station manufacturers uses a slightly different technique. One may pick the strongest signal of the inputs A1 and A2 to output, another may align the phase of the two signals and sum them to produce an output, and a third may use

maximal ratio combining which aligns the phase and weights of the two signals in proportion to their signal-to-noise ratio before summing them to produce an output.

The diversity combination circuitry 830 then provides its output to signal quality circuitry 832. Quality is determined based on a signal to interference and noise ratio calculation, which is discussed below. If signal quality is improved with respect to the output of the diversity combination circuitry, then the signal quality measurement circuitry 832 can cause the switch 833 to select the output of the selected port 144a or 144b. If signal quality is not improved and the interference reduction unit circuit 840 is in set-on mode, then the signal quality circuitry 832 can cause the interference reduction unit circuit 840 to select another channel. If signal quality is not improved and the interference reduction unit circuit 840 is in copy mode, then the signal quality circuitry 832 can cause the switch 833 to select the output of the antennas instead of the output of the selected port. This causes the site radios to apply their own diversity combination. If the interference reduction unit circuit 840 is in the copy mode and the signal quality is not improved for more than a prescribed interval, then the interference reduction circuit 840 switches to the set-on mode and selects another channel.

In addition to comparing diversity combination with the output of the signal using weights 816a, 816b, 816c, and 816d, which are from the current epoch, signal quality is also compared with signals generated from the analogous weights from the prior epoch. Thus, a selection is made between five possible signals: the diversity combination output, two ports with signals based on weights from the current epoch, and two ports with signals based on weights from the prior epoch.

Prior to output, the selected signal is scaled to have no gain change as it passes through the system.

The following is a description of a method of reducing interference that can be applied in the circuitry described above or as software in a

microcomputer. Cellular base station equipment includes a number of different channels. In order to conserve equipment resources, the present embodiment of the invention selectively applies adaptive beamforming to channels on which interference more likely will be reduced by the adaptive beamforming. The set-on mode of operation helps to accomplish this goal. The set-on mode of operation evaluates cellular channels. It identifies a channel on which interference more likely will be reduced by adaptive beamforming, and switches to the copy mode of operation in which it applies adaptive beamforming to that channel.

The set-on mode in accordance with an embodiment of the invention includes a collection of progressively more perceptive tests. The first tier of tests is accomplished relatively quickly. Only if the first tier of tests are passed does the method apply the second, more time consuming tier of tests. This method allows hardware to be used for other channels instead of being used on a channel not needing interference reduction. Figure 10 shows the set-on mode of operation.

Sniff the transmitter signal in step 1010 in order to determine the base station channel plan. Perform this step 1010 until the full channel complement is discovered. In subsequent steps the set-on method services only channels in the base station channel plan.

Select a channel from among channels in the base station channel plan in step 1012. For the selected channel, sniff the transmitter signal 1014. If the transmitter 1016 is off, then assume there is no signal of interest on this channel and return control to the step of selecting a channel from the system plan 1012. This time, a different channel is selected from the channel plan. Next perform a first tier of tests for the selected channel in step 1016. If these tests 1018 are not passed, then again return to the step of selecting a channel from the system plan 1012. If the first tier tests 1018 are passed, then perform a second tier of tests 1020. If the second tier of tests 1020 is not passed, then return to the step selecting a channel from the system plan 1012, this time selecting a different

channel from the one previously selected. If the second tier of tests 1020 is passed, then apply adaptive beamforming 1022.

The first tier tests 1018 are illustrated in Figure 11. First take n 3.0 ms data blocks in step 1110. In one embodiment n = 2; however, n could also have other values such as 1, 3, 4, 5 or other values.

Then perform diversity combination (DC) 1112 followed by the computation of DC signal parameters 1114. DC signal parameters include average signal power for two 3.0 ms data blocks (DC_POW_1 and DC_POW_2 respectively); signal-to-interference and noise estimates for those same data blocks (DC_SINR_1 and DC_SINR_2 respectively); and a crude estimate of the frequency of the supervisory audio tone for the DC output (DC_SAT_FREQ).

In step 1116, the signal power estimates, DC_POW_1 and DC_POW_2, are compared against a DC power set-on threshold (DC_POW_THRESHOLD). If the threshold criteria are not met the from step 1116, proceed to 1122 and fail the first tier tests 1018. Otherwise, continue to step 1118. The criteria for step 1116 are:

(DC_POW_1 greater than DC_POW_THRESHOLD) and
(DC_POW_2 greater than DC_POW_THRESHOLD)

In step 1118, compare the SAT frequency, DC_SAT_FREQ, against the frequency for the signal of interest, SOI_SAT_FREQ. If they are not equal, continue to step 1120 pass the first tier tests because this is an indication of interference. Otherwise check the two signal-to-noise measurements against a threshold. If both measurements are below the threshold, then continue to step 1120 and pass the first tier tests because this is again an indication of interference. If neither of these conditions are met, then from step 1118 proceed to 1122 and fail the first tier tests 1018. The criteria for step 1118 are:

DC_SAT_FREQ not equal to SOI_SAT_FREQ or
(DC_SINR_1 less than DC_SINR_THRESHOLD and
DC_SINR_2 less than DC_SINR_THRESHOLD)

The goal is to complete the first tier in a relatively short period of time (6 to 10 ms) and then go on to the next channel if the first tier tests are failed or the next tier if the first tier tests are passed.

The second tier tests 1020 are illustrated in Figure 12. First a 33 ms data sample is collected from the selected channel in step 1210. This data sample has a long enough duration so that SAT tones can be accurately identified within it. In another embodiment, a smaller data sample, e.g. 10 ms could be taken, provided that SAT tones could be identified within that data sample. Next, in step 1212, apply adaptive beamforming to the data sample to produce outputs on port 1 and port 2. In step 1214 apply FM discrimination to ports 1 and 2 to determine SAT tone frequencies for both ports.

In steps 1216, 1218, and 1120 check the SAT tone frequencies. Specifically in step 1216, check how many SAT tones are present in the two ports. If there are none present, then fail the second tier tests by moving to step 1226. Otherwise, continue to step 1218.

In step 1218, check for the presence of the signal of interest (SOI) in at least one of the two ports. If the SOI is not present, then fail the second tier tests by moving to step 1226. Otherwise, continue to step 1220.

In step 1220, check whether the SOI is present in both ports (a "co-SAT" situation). If a co-SAT situation exists, then fail the second tier tests by moving to step 1226. Otherwise, continue to step 1222.

In step 1222, check for improvement in signal quality between the beamformer output compared to the diversity combination (DC) output. If there is no improvement in quality, then fail the second tier tests by moving to step 1226. Otherwise, pass the second tier tests by moving to 1224.

The test for quality improvement 1222 is made using the following measurements: The diversity combiner signal-to-interference and noise ratio (DC_SINR) and the signal-to-interference and noise ratio of the beamformer port containing the signal of interest (SOI_SINR). These measurements are

compared against an improvement threshold to determine if there is improvement in quality.

The logic for the quality improvement determination is shown in Figure 13. In step 1310, check the SAT tone of the diversity combination output. If the DC SAT tone is not the SOI SAT, then this is an indication that the signal at the DC output is interference. Since it has already been determined that the beamformer contains the SOI, then determine that there is a quality improvement and move to step 1316. Otherwise, continue with step 1312.

In step 1312, check the signal-to-interference and noise levels at the DC and beamformer outputs. If there is quality improvement, then move to step 1316. Otherwise, move to step 1314.

Figure 14 shows the method of applying adaptive beamforming that is indicated in step 1022 of figure 10. First in step 1410 collect channelized data from each antenna for a length of time that is shorter than one divided by the fade rate, i.e. (1/ fade rate). A fade rate of 100 Hz is assumed, thus collection of data for beamforming for a 1 to 10 ms duration may be performed. A data collection sample in the range of 1.5 to 6 ms or other range or duration is also possible. Further, a fade rate of 1kHz and corresponding data collection sample duration (the inverse of the fade rate) is possible.

In step 1412 apply least squares minimization with a linear fit, or, alternatively, MT-LSCMA with linear fit processing to compute beamforming weights. MT-LSCMA algorithm is described in the Agee paper. The goal of using least squares minimization with linear fit is to separate 2 or more different signals coming from different angles of arrival to an antenna array onto 2 or more output ports such that each output port contains a unique signal. This is accomplished by the algorithm (in the case of only 2 ports) by generating weights for port 1 such that a sensitivity null is placed in the direction of the second strongest signal and weights for port 2 such that the sensitivity null is placed in the direction of the strongest signal. It is appreciated that other

algorithms could also be employed to calculate weights in order to isolate signals from different directions.

Least squares minimization can make use of an initial set of weights if they are available. If no initial set of weights is available, as is the case with the set-on procedure, the weights are initialized by setting w11 (816a) and w22 (816d) to 1 and weight w12 (816b) and w21 (816c) to 0. This initialization can cause least squares minimization with linear fit to output the largest signal (i.e. the most powerful signal) at port 1, and the second largest at port 2. Since the largest signal could be either the signal of interest or an interferer, the output of each port must be examined by external circuitry to determine whether it is the signal of interest based on the SAT. For the set-on operation, 8 iterations of the least squares minimization with linear fit are used.

If an initial set of weights is available for a channel, as is the case in the application of the continuous copy mode where new weights are computed every 33 ms, the least squares minimization with linear fit is initialized with the previous signal-of-interest weights in port 1. Port 1 usually provides the strongest signal estimate because of the sequential way the least squares minimization with linear fit works internally, first computing the port 1 output and then port 2. In continuous copy mode, since there is an initial set of weights, only 2 iterations of the least squares minimization with linear fit are used.

It is appreciated that variants of this copy procedure may be used to take particular advantage of the assumption that a distant interferer (one outside the local cell) will change its direction of arrival very little in the 33 ms between successive weight determinations. Thus averaging of the generalized arrival vector of the interferer (in the two-antenna case this is just the ratio of the two complex weights of port 2) may be done to increase the accuracy of the interferer's weights and its direction in the presence of measurement noise and interference. This averaging may be used to provide a better initial weight vector for port 2, which produces the interferer.

Another application of the averaging of the interferer direction of arrival is to produce a better initial set of weights for the signal of interest (port 1). In applications with fast 100Hz Rayleigh fading on the local signal, the signal of interest can be expected to arrive from a different electrical direction every 10 ms. Since the new weights are computed every 33 ms, the past set of weights for the signal may provide a relatively poor initialization for port 1. In this situation it would be better to provide an initialization which, at least, has little sensitivity for the interferer. From the averaged (or even non-averaged) estimate of the interferer's direction of arrival, a set of weights with a deep sensitivity null for the interferer can be easily determined and provided as an initialization point for the port 1. In this way, combined with the method of the previous paragraph, good initialization weight sets for both ports 1 and port 2 can be provided. It is appreciated that such variants could be applied to the disclosed method.

Next, in step 1414 compute the outputs of both ports over a 33 ms time interval. This time interval is known as an epoch. This time interval is selected in order to allow time to identify the signal of interest by the SAT. The SATs could be at three possible frequencies: 5970 Hz, 6000 Hz, and 6030 Hz. Because these frequencies are separated by 30 Hz, they can be separated in a standard linear filter in 1/30th of a second, or 33 ms. Using this technique, then, it takes 33 ms to identify a signal of interest. Other techniques may be used for quicker recognition times.

Next, in step 1416 determine which port contains the signal of interest and output that port from the port select switch. Determine which port contains the signal of interest by looking at the SATs on the various ports and comparing the SATs with the expected SAT of the signal of interest. It is appreciated, however, as indicated above, that other techniques could be used to identify a signal of interest other than by SAT. New weights are calculated in each epoch. Additionally, weights from the previous epoch are retained and also used to output signals to various ports. Thus, there are two sets of ports, and in

each set of ports one port is selected which contains the signal of interest based on the SAT of the signal of interest. In addition to using the weights of the previous epoch, weights from other prior epochs may also be used and the outputs based on those weights may also be selected.

Next, in step 1418 make sure that the adaptive beamforming (i.e., the combination of the previous steps) is performing better than the conventional diversity combiner by measuring signal quality. Output the better of the conventional diversity combiner and the output of the adaptive beamforming. Additionally, compare the adaptive beamforming outputs between the old weights, from the previous epoch, and the new weights, from the current epoch. Select among the diversity combiner, the adaptive beamforming output based on the old weights, and the adaptive beamforming output based on the new weights. If adaptive beamforming fails to provide an improved signal for as long as one second, then stop adaptive beamforming for the selected channel and select a different channel. This duration, which the system allows before stopping adaptive beamforming for the selected channel, is user-setable and could thus be set to values other than one second. Wait for a silent period of 33 ms, however, before dropping the channel and selecting a different signal. This wait period helps to avoid corrupting a call when switching from the adaptive beamforming output back to the ordinary diversity combining output. This is especially important in data calls.

Figure 15 shows an illustrative flow chart of a method of applying adaptive beamforming to a channel in a wireless cellular communication system using linear fit according to an embodiment of the invention. In order to reduce interference, the signal is separated into different signals on different ports using a least squares minimization technique. The output of this technique is different signals on different ports. The technique involves operations on the input data and the calculation of weights which are then applied to the input data in order to separate the input data onto the various ports. The number of weights in each set of weights corresponds to the number of antennas and also the number of

output ports. The number of sets of weights also corresponds to the number of antennas.

Iteratively apply a least squares minimization with a linear fit to the input data from the two antennas until the set of weights is arrived at. Then, use these weights to separate signals and output the signals to different ports. Additionally, weights that were calculated in the previous epoch are applied to the data to separate the signals onto additional output ports. Then, choose among the output ports from the new weights, old weights, and diversity combination. In choosing between signals consider the presence of the correct SAT and the signal to noise and interference ratio.

Referring to Figure 15, first sample data from the antennas (block 1502). The input data is a 3 ms sample of data points from the two antennas. Each data point is a complex number. For each antenna, a total of 128 or 129 complex data points is included in this sample. Next, initialize a counter, which is used in order to count the iterations (block 1504).

For discussion of this technique, please refer to the following notation:

$x(m)$	the M element vector input data
$y_k(m)$	output of the k^{th} port (after beamforming)
$y(m)=[y_k(m)]_0^{M-1}$	M element vector array output signal
$\{w_k\}_0^{M-1}$	beamformer weights for each output port k
$y(m)=W^H x(m)$	the input-output matrix transformation

Define the block correlation estimate computed over the N-long averaging interval $[n(N-1),nN]$:

$$\hat{R}_{xx}(n)=\frac{1}{N}\sum_{m=0}^{N-1} x(nN-m)x^H(nN-m)$$

(block 1506).

Next determine the complex-limited signal scaled by a linear fit on the k^{th} output port (block 1508):

$$\hat{R}_{xr_k}(n) = \frac{1}{N}\sum_{m=0}^{N-1} r_k\,(nN - m)x^H\,(nN - m)$$

where

$$r_k(m) = \frac{y_k(m;n-1)}{|y_k(m;n-1)|}\,a_k(m;n-1)$$

where, $a_k\,(m;n-1)$ is the resultant linear fit vector using standard linear regression techniques (fitting a straight line to the available data), and

$$y_k\,(m;n-1) = w_k^H\,(n-1)x(m)$$

Update the beamformer weights with the block correlation estimate and complex limited signal via a block updating operation (block 1510):

$$w_k(n) = \hat{R}_{xx}^{-1}(n)\hat{R}_{xr_k}(n)$$

Next increment counter (block 1512). If the counter is less than the total number of iterations minus one, then return to block 1506. When the counter is equal to the total number of iterations minus one, this represents the second to the last iteration. Thus, blocks 1518-1522 are not performed on the last iteration. If the counter equals N, where N is the total number of iterations, then the last iteration is complete (block 1516). When the last iteration is complete, then go to block 1524 to choose among the diversity combination, old weights, and new weights (block 1524). For the set on mode, the total number of iteration for one epoch, N, is 8. For the copy mode, N is 2 iterations.

Next, if it is not the last or second to last iteration, perform a soft orthogonalization. For a description of one technique of soft orthogonalization, see the Agee paper, which is incorporated herein by reference. In particular, see equations 7-10 of the Agee paper. First determine the hard orthogonalization processor weights (block 1518) that minimize the least-squares error. Step through the output ports k = 0 to m - 1:

$$\hat{w}_k(n)_{k=0}^{M-1}$$

$$\left\langle |\hat{y}_k(nN) - y_k(nN)|^2 \right\rangle_N , \quad \hat{y}_k(m) = \hat{w}_H^k(n) x(m)$$

subject to the constraint $\left\langle \hat{y}_k(nN) y_l(nN) \right\rangle_N = 0$ for every $l < k$, using a standard Gram-Schmidt Orthogonalization (GSO) procedure.

Next, determine the softening parameter $\lambda_k(n)$ that satisfies the global orthogonalization test (block 1520):

$$\bar{\epsilon}_k \triangleq \frac{\left\langle |\hat{y}_k(nN) - y_k(nN)|^2 \right\rangle_N}{\left\langle |\hat{y}_k(nN)|^2 \right\rangle_N} \quad < \quad \epsilon_{max}$$

$$\tilde{y}_k(m) \triangleq \lambda_k(n) y_k(m) + [1 - \lambda_k(n)] \hat{y}_k(m)$$

Next, determine the soft orthogonalized processor $\{\tilde{w}_k(n)\}_{k=0}^{M-1}$ weights (block 1522).

$$\tilde{w}_k(n) = \lambda_k(n) w_k(n) + [1 - \lambda_k(n)] \hat{w}_k(n).$$

Use weights $\{\tilde{w}_k(n)\}_{k=0}^{M-1}$ as the processor weights over the next block of processing.

Compute the softening parameter $\lambda_k(n)$ as follows:

$$\lambda_k(n) = \sqrt{\frac{\varepsilon_k(n)[1 - \epsilon_k(n)]}{\epsilon_k(n)[1 - \varepsilon_k(n)]}} ,$$

where $\varepsilon_k(n)$ is the *target* orthogonalization distance (see above formula for ε_k) and $\epsilon_k(n)$ is the unconstrained orthogonalization distance obtained by setting $\tilde{y}_k(m) = y_k(m)$ in that formula.

After determining the soft orthogonalization processor weights, return to block 1506 to begin another iteration and determine the block correlation estimate with the data.

In block 1524, it is determined whether to use the diversity combination, the old weights, or the new weights for the remainder of the epoch. In the case of set-on mode, old weights are not available and are not selected. The selection between diversity combination, old weights, and new weights is based on SAT's and a signal to noise and interference ratio, which is discussed below. Next, apply for the remainder of the epoch either the diversity combination, old weights, or new weights (block 1626).

Figure 16 shows an illustrative diagram of a signal including a portion used for a data sample. Figure 16 displays a signal 1602 which exhibits fading caused by the multipath. Signals from cellular users are received at their serving base station via multiple indirect paths (multipath) as opposed to direct line-of-sight reception. This results in mutual interference between signal components on the multiple paths and causes amplitude variations on the total received signal at the cell site antennas. Furthermore, the cellular emitters may be in vehicles whose movement can cause Doppler shifts of up to 100 Hz, resulting in 100 Hz Rayleigh fading on the total received signal envelope and, in

addition, random changes in the apparent angle-of-arrival of the signal, even without interference. As indicated above, a linear fit is applied in the least squares minimization technique. As shown, linear approximation 1608 follows the fading portion 1604 of signal 1602. Thus, the linearization helps the least squares minimization to minimize variation caused by the presence of interference, rather than fading.

Signals from five different output ports are considered to help select the port having the signal of interest. As mentioned earlier, the ports include the diversity combination output, the two ports containing the outputs with the old weights, and the two ports containing the outputs with the new weights. In selecting between all of these ports, first it is determined which port among the two ports with the old weights is to be considered, and which port among the two ports with the new weights is to be considered.

Table 1 illustrates the selection between ports for a set of weights from one epoch. The selection is performed as follows: For the two ports using the new weights, for example, one port is designated as the signal of interest port and the other port is designated as the interferer port. If the signal of interest port contains the right SAT, then the signals are not swapped between the ports. If the signal of interest port contains no SAT or the wrong SAT, and the right SAT is on the interferer port, then the ports are swapped. The same selection is applied for the two ports output using old weights.

	SOI Port	Interferer Port	Action	Final State of SOI Port
1	RIGHT_SAT	RIGHT_SAT	NO_SWAP	RIGHT_SAT
2	RIGHT_SAT	WRONG_SAT	NO_SWAP	RIGHT_SAT
3	RIGHT_SAT	NO_SATS	NO_SWAP	RIGHT_SAT
4	WRONG_SAT	RIGHT_SAT	SWAP	RIGHT_SAT
5	WRONG_SAT	WRONG_SAT	NO_SWAP	WRONG_SAT
6	WRONG_SAT	NO_SATS	SWAP	NO_SATS
7	NO_SATS	RIGHT_SAT	SWAP	RIGHT_SAT
8	NO_SATS	WRONG_SAT	NO_SWAP	WRONG_SAT
9	NO_SATS	NO_SATS	NO_SWAP	NO_SATS

Table 1

Next, after a particular port is selected among the old weights and the new weights, then a selection is made between the diversity combination (DC) output, the old weights, and the new weights, as shown in Table 2. This selection is made based on the SAT and the signal to interference and noise ratio (SINR). The right SAT is favored over the wrong SAT or over no SAT (e.g., row 2, preferring DC or old weights over new weights). A higher SINR is favored over a lower SINR (e.g., row 2, preferring DC or old weights based on SINR). If two or more right SATs are present, then a selection may be made based on SINR. If all three ports have the wrong SAT (e.g., row 14) or all three ports have no SAT (e.g., row 27), then the last state may be chosen, where the last state is either the old weights or the diversity combination depending on which of the two was used in the previous epoch. If the diversity combination and the old weights have the wrong SAT and the new weights produce no SAT, then use the new weights (e.g., row 15).

	DC	Old Weights	New Weights	OUTPUT
1	Right SAT	Right SAT	Right SAT	maximum SINR out of the (DC, Old ABF, New ABF)
2	Right SAT	Right SAT	Wrong SAT	maximum SINR out of the (DC, Old ABF)
3	Right SAT	Right SAT	No SAT	maximum SINR out of the (DC, Old ABF)
4	Right SAT	Wrong SAT	Right SAT	maximum SINR out of the (DC, New ABF)
5	Right SAT	Wrong SAT	Wrong SAT	DC
6	Right SAT	Wrong SAT	No SAT	DC
7	Right SAT	No SAT	Right SAT	maximum SINR out of the (DC, New ABF)
8	Right SAT	No SAT	Wrong SAT	DC
9	Right SAT	No SAT	No SAT	DC
10	Wrong SAT	Right SAT	Right SAT	maximum SINR out of the (DC, New ABF)
11	Wrong SAT	Right SAT	Wrong SAT	Old weights
12	Wrong SAT	Right SAT	No SAT	Old weights
13	Wrong SAT	Wrong SAT	Right SAT	New weights
14	Wrong SAT	Wrong SAT	Wrong SAT	Last State
15	Wrong SAT	Wrong SAT	No SAT	New weights
16	Wrong SAT	No SAT	Right SAT	New weights
17	Wrong SAT	No SAT	Wrong SAT	Old weights
18	Wrong SAT	No SAT	No SAT	Old weights

	DC	Old Weights	New Weights	OUTPUT
19	No SAT	Right SAT	Right SAT	maximum SINR out of the (DC, New ABF)
20	No SAT	Right SAT	Wrong SAT	Old weights
21	No SAT	Right SAT	No SAT	Old weights
22	No SAT	Wrong SAT	Right SAT	New weights
23	No SAT	Wrong SAT	Wrong SAT	Last State
24	No SAT	Wrong SAT	No SAT	Last State
25	No SAT	No SAT	Right SAT	New weights
26	No SAT	No SAT	Wrong SAT	Last State
27	No SAT	No SAT	No SAT	Last State

Table 2

The signal to noise and interference ratio can be measured based on amplitude or based on power. When measured based on amplitude, the signal to noise and interference ratio (SINR) is determined as follows:

$$SINR = 20 \cdot \log \left[\frac{\frac{1}{N} \sum_{m=0}^{N-1} a(m)}{\sqrt{\frac{1}{N-1} \sum_{m=0}^{n-1} [v(m) - a(m)]^2}} \right]$$

where $v(m)$ = the signal vector incident on an antenna or the diversity combiner output, depending on how input SINR is defined, and $v(m) = y_k(m)$ if k^{th} port output SINR is being measured.

In order to arrive at the correct SINR estimate, a linear fit to the received data (see Figure 11, block 1118) is used. The linear fit helps to mitigate the

effects of multipath fading on the otherwise constant modulus signals, thus presence and relative amplitude of interference is recognized as deviations from such Rayleigh-faded signals.

The signal to noise and interference ratio may be calculated based on the power of the signal as follows:

Define:

$$\bar{p}=\frac{1}{N}\sum_{m=0}^{N-1} a_{pwr}(m)$$

and

$$\sigma=\sqrt{\frac{1}{N-1}\sum_{m=0}^{N-1}[v_{pwr}(m)-a_{pwr}(m)]^2}$$

where $v_{pwr}(m) = v^*(m)\, v(m)$ and $v(m)$ is as defined above and * in $v^*(m)$ stands for the complex conjugate. Also $a_{pwr}(m)$ is an analogous to the above linear fit vector, except the fit is done to the signal power envelope.

Thus,

$$SINR=10\cdot\log\left[\frac{\bar{p}+\sqrt{\bar{p}^2-2\sigma^2}}{\bar{p}-\sqrt{\bar{p}^2-2\sigma^2}}\right]$$

It is appreciated that an alternate implementation of the invention could completely eliminate tier 1 tests and could achieve sufficient selectivity in tier 2 alone by requiring that the adaptive beamforming is performing better than conventional diversity combining by more than a setable improvement, greater than zero dB (for example, 3dB). The larger this required improvement is set, the fewer channels would qualify at any one time, limiting the number of adaptive beamforming units required to service all channels. This alternative would make the test more robust at the expense of taking longer to perform since it would omit the screening of the shorter tier 1 tests.

Next, the above steps starting with 1410 are repeated for the next epoch, as indicated in step 1420. This process continues, with the goal of reducing interference on the selected channel.

Although the description above showed a system where the base station has two receive antennas, the base station may be implemented with more than two receive antennas (for example, 3, 4, 5, 6, or a greater number of antennas). An adaptive beamforming and scanning processor in such embodiments would have a number of ports corresponding to the number of antennas.

Moreover, although an embodiment of the invention may be implemented in an analog cellular system, it will be appreciated that embodiments of the invention may be implemented in other forms of mobile communication systems such as digital cellular, and personal communications services (PCS), for example.

Some of the discussion above involves an embodiment of the invention that scans different channels and applies interference reduction only to selected channels. It is appreciated, however, that the invention includes embodiments in which separate interference reduction circuitry is provided to each channel. For example, interference reduction circuitry or processing could be placed into or occur in the base station receivers, where separate interference reduction units are provided to the channels.

The foregoing description of embodiments of the invention has been provided for the purposes of illustration and description. It is not intended to be exhaustive or to limit the invention to the precise form disclosed. Many modifications and variations will be apparent. The embodiments were chosen and described in order to explain the principles of the invention and its practical application, thereby enabling others to understand the invention for various embodiments and with various modifications as are suited to the particular use contemplated. It is intended that the scope of the invention be defined by the following claims and their equivalents.

WHAT IS CLAIMED IS:

1. A method of reducing interference on a channel in a mobile communication system having an array of at least two antennas including at least a first antenna and a second antenna, the method comprising:

receiving a first waveform on the channel on the first antenna;

receiving a second waveform on the channel on the second antenna;

adaptively combining the first waveform and the second waveform into a first candidate signal;

adaptively combining the first waveform and the second waveform into a second candidate signal; and

selecting among the first candidate signal and the second candidate signal based on a supervisory audio tone.

2. The method of claim 1, including:

selecting among the first candidate signal and the second candidate signal based on a function of interference and noise in the first candidate signal and the second candidate signal.

3. The method of claim 1, including:

selecting among the first candidate signal and the second candidate signal and a diversity combination output based on the supervisory audio tone and a signal to interference and noise ratio.

4. The method of claim 1, wherein the supervisory audio tone comprises a band of frequencies selected from the group of:

frequencies centered at 5970 Hz,

frequencies centered at 6000 Hz, and

frequencies centered at 6030 Hz.

5. The method of claim 1, wherein adaptively combining the first waveform and the second waveform into a first candidate signal comprises:

obtaining a first sample from the first waveform;

obtaining a second sample from the second waveform;

in a digital system determining weights based on the first sample and the second sample; and

applying the weights to the first waveform and the second waveform.

6. The method of claim 5, wherein the first waveform has a fade rate and wherein the first sample has a duration less than the inverse of the fade rate and the second sample has a duration less than the inverse of the fade rate.

7. The method of claim 6, wherein the fade rate comprises 1 kHz.

8. The method of claim 5, wherein the first sample has a duration in the range of 1 ms to 10 ms.

9. The method of claim 5, wherein the first sample has a duration in the range of 1.5 ms to 6 ms.

10. The method of claim 1, comprising:

providing a diversity combination output based on the first waveform and the second waveform; and

selecting among the first candidate signal, the second candidate signal, and the diversity combination output based on a function of interference and noise and on the supervisory audio tone.

11. The method of claim 10, the function comprising a signal to interference and noise ratio.

12. The method of claim 10, the function comprising a function of variance from a linear fit to the waveforms in relation to average magnitude of the waveforms.

13. The method of claim 1, the channel comprising a frequency division multiplexed channel.

14. A method of signal processing in a mobile communication system, the mobile communication system including an array of at least a first antenna and a second antenna and operating on a plurality of channels and using supervisory audio tones, the method comprising:

receiving a first waveform on a first channel on the first antenna;

receiving a second waveform on the first channel on the second antenna;

obtaining a first sample from one or both of the first and second waveforms;

measuring signal quality based on the first sample;

if the signal quality is below a particular threshold, then

obtaining a second sample from the first waveform, the second sample having a duration at least long enough to allow for distinguishing the supervisory audio tones;

combining the first waveform and the second waveform into a first candidate signal;

combining the first waveform and the second waveform into a second candidate signal; and

determining whether to apply interference reduction on the channel based on the first candidate signal, the second candidate signal, and a supervisory audio tone in the second sample;

wherein the first sample has a duration shorter than the duration of the second sample.

15. The method of claim 14, comprising:

if the signal quality is not below the particular threshold, then

receiving a third waveform on a second channel on the first antenna;

receiving a fourth waveform on the second channel on the second antenna; and

determining whether to apply interference reduction to the second channel.

16. The method of claim 14, measuring signal quality based on the first sample comprising:

measuring noise.

17. The method of claim 14, measuring signal quality based on the first sample comprising:

measuring a ratio of signal to interference and noise.

18. The method of claim 14, comprising selecting among a diversity combination, the first candidate signal, and the second candidate signal if it is determined to apply interference reduction on the channel in the determining whether to apply interference reduction.

19. The method of claim 18, the selecting based on the supervisory audio tone and a function of noise and interference.

20. A method of reducing interference in a mobile communication system having an array of at least two antennas, the method comprising:

receiving waveforms on the antennas;

obtaining a sample from the waveforms;

combining the waveforms into a first candidate signal and a second candidate signal based on minimizing variance of a linear fit to the candidate signals; and

selecting among the first candidate signal and the second candidate signal.

21. The method of claim 20, wherein the sample includes a plurality of analog to digital converter outputs from the array of at least two antennas from a duration less than an inverse of a fade rate of the waveforms.

22. The method of claim 20, combining the waveforms into a first candidate signal and a second candidate signal comprising:

determining a complex limited signal from the sample with a linear fit.

23. The method of claim 22, combining the waveforms into a first candidate signal and a second candidate signal comprising:

determining a block correlation estimate from the sample; and

updating a set of weights based on the block correlation estimate and the complex limited signal.

24. The method of claim 23, combining the waveforms into a first candidate signal and a second candidate signal comprising:

determining a hard orthogonalization based on the sample;

determining a softening parameter; and

determining a soft orthogonalization based on the set of weights, the hard orthogonalization and the softening parameter.

25. The method of claim 20, the sample having a duration shorter than the inverse of a fade rate of the waveforms;

26. The method of claim 25, comprising selecting a signal among the first candidate signal and the second candidate signal based on a supervisory audio tone.

27. The method of claim 26, comprising selecting among the first candidate signal and the second candidate signal based on a function of noise.

28. The method of claim 26, comprising selecting among the first candidate signal, the second candidate signal, and a diversity combination signal based on a function of noise.

29. A method of reducing interference in a mobile communication system having an array of at least two antennas, the method comprising:

receiving waveforms on the antennas;

obtaining a first sample from the waveforms;

determining a first set of weights based on a first sample;

after obtaining the first sample, obtaining a second sample from the waveforms;

determining a second set of weights based on the second sample;

applying the first set of weights to the waveforms to yield a first candidate signal and a second candidate signal;

applying the second set of weights to the waveforms to yield a third candidate signal and a fourth candidate signal; and

selecting among the first candidate signal, the second candidate signal, the third candidate signal, and the fourth candidate signal.

30. The method of claim 29, selecting among comprising selecting based on supervisory audio tone and a function of noise and interference.

31. The method of claim 30, selecting among comprising selecting among a diversity combination output.

32. A method of reducing interference in a mobile communication system, the mobile communication system operative on a plurality of channels, the method comprising:

testing a first channel for signal quality;

if signal quality of the first channel is below a predetermined threshold, then

applying interference reduction to the first channel;

if signal quality of the first channel is not below the predetermined threshold, then

testing a second channel for signal quality without applying interference reduction to the first channel, and

if signal quality of the second channel is below the predetermined threshold, then

applying interference reduction to the second channel.

33. The method of claim 32, wherein testing the first channel for signal quality comprises:

measuring a ratio of signal to interference and noise.

34. The method of claim 33, comprising:

if applying interference reduction to the first channel does not improve signal quality relative to a diversity combiner output, then

testing the second channel for signal quality without further applying interference reduction to the first channel; and

if signal quality of the second channel is below the predetermined threshold, then

applying interference reduction to the second channel.

35. The method of claim 33, wherein applying interference reduction to the first channel comprises:

receiving a first waveform on a first antenna;

receiving a second waveform on a second antenna;

combining the first waveform and the second waveform to yield a first candidate signal and a second candidate signal; and

selecting among the first candidate signal and the second candidate signal.

36. The method of claim 35, wherein applying interference reduction comprises selecting among the first candidate signal and the second candidate signal based on a supervisory audio tone.

37. A method of measuring signal quality in a mobile communications system, the mobile communications system operating on waveforms, the waveforms tending to fade, the method comprising:

measuring variance from a linear fit to the waveforms in relation to average magnitude of the waveforms in the sample.

38. A method of reducing interference in an analog mobile communications system base station which does not use beamforming, the base station including radios and at least two receive antennas, the method comprising:

inserting a digital signal processor between the antennas and the radios;

using the digital signal processor to apply beamforming to waveforms received from the antennas to yield at least a first candidate signal and a second candidate signal;

selecting among the first candidate signal and the second candidate signal; and

outputting a selected signal to the radios.

39. The method of claim 38, wherein selecting among the first candidate signal and the second candidate signal comprises:

selecting based on a supervisory audio tone.

40. The method of claim 38, wherein selecting among the first candidate signal and the second candidate signal comprises:

selecting among a diversity combination output, the first candidate signal, and the second candidate signal.

41. The method of claim 38, wherein selecting among the first candidate signal and the second candidate signal comprises:

selecting based on a signal to interference and noise ratio.

42. The method of claim 38, selecting comprising selecting based on a supervisory audio tone.

43. The method of claim 38, comprising:

measuring signal quality on a first channel;

applying beamforming to the first channel if signal quality on the first channel is below a particular threshold; and

if signal quality is not below the particular threshold,

not applying beamforming to the channel,

measuring signal quality on a second channel, and

applying beamforming to the second channel if the signal quality on the second channel is below the particular threshold.

44. The method of claim 38 including coupling the digital signal processor to existing coaxial cables that are coupled to the antennas and the radios.

45. An interference reduction system for use in a mobile communications system base station, the base station including at least a first antenna and a second antenna, the interference reduction system comprising:

a resource that receives a first waveform on a channel from the first antenna;

a resource that receives a second waveform on the channel from the second antenna;

a resource that adaptively combines the first waveform and the second waveform into a first candidate signal;

a resource that adaptively combines the first waveform and the second waveform into a second candidate signal; and

a resource that selects among the first candidate signal and the second candidate signal based on a supervisory audio tone.

46. The interference reduction system of claim 45, including:

resources that select among the first candidate signal and the second candidate signal and a diversity combination output based the supervisory audio tone and a signal to interference and noise ratio.

47. The interference reduction system of claim 45, including:

resources that combine the waveforms based on minimizing variance of a linear fit to the waveforms.

48. A mobile communications system base station comprising:

an array of antennas including at least a first antenna and a second antenna;

radios;

a circuit coupled between the array of antennas and the radios, the circuit including:

a resource that receives a first waveform on a channel from the first antenna;

a resource that receives a second waveform on the channel from the second antenna;

a resource that adaptively combines the first waveform and the second waveform into a first candidate signal;

a resource that adaptively combines the first waveform and the second waveform into a second candidate signal; and

a resource that selects among the first candidate signal and the second candidate signal based on a supervisory audio tone and outputs a selected signal to the radios.

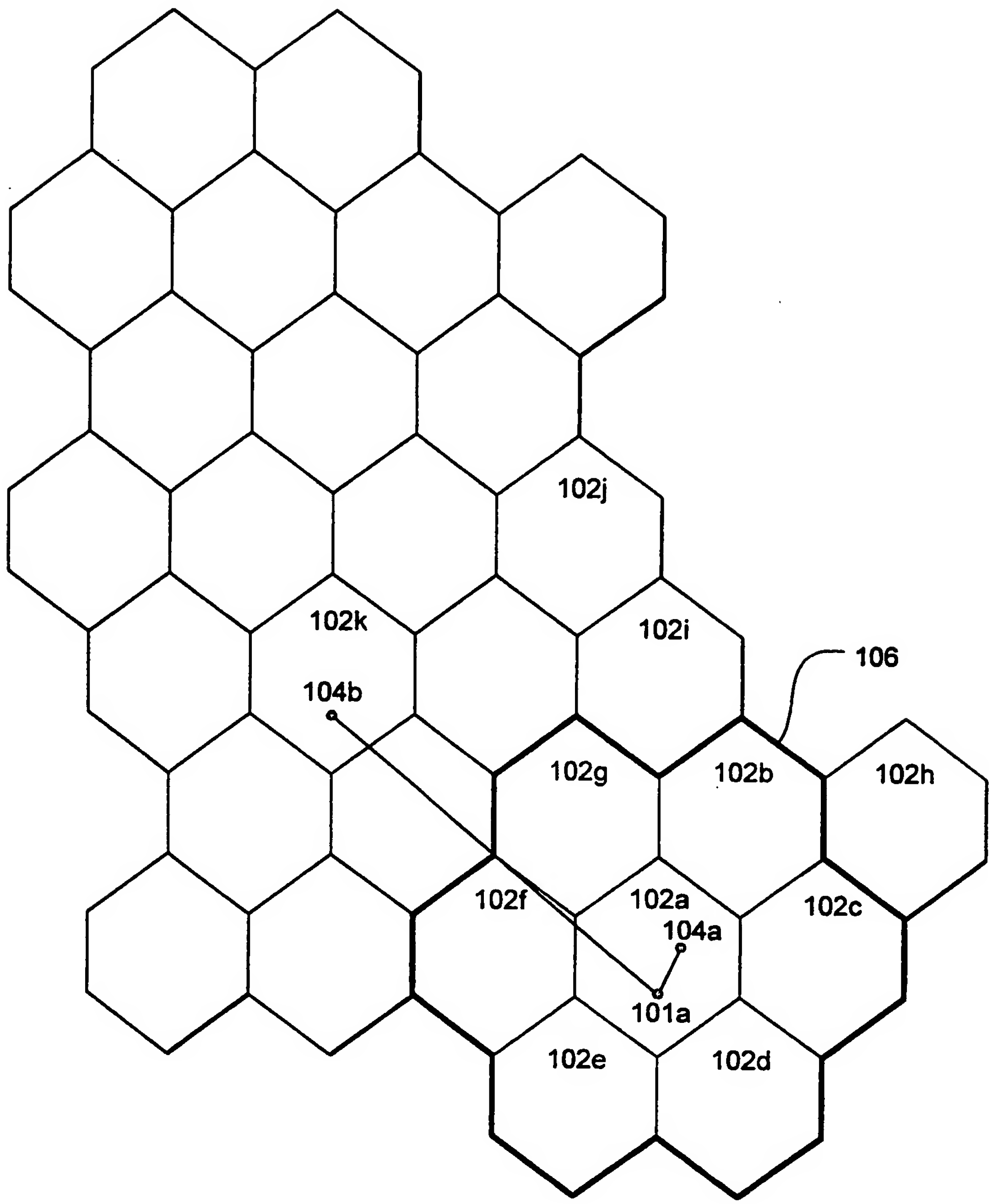

102j
102k
102i
106
104b
102g
102b
102h
102f
102a
102c
104a
101a
102e
102d

FIG. 1

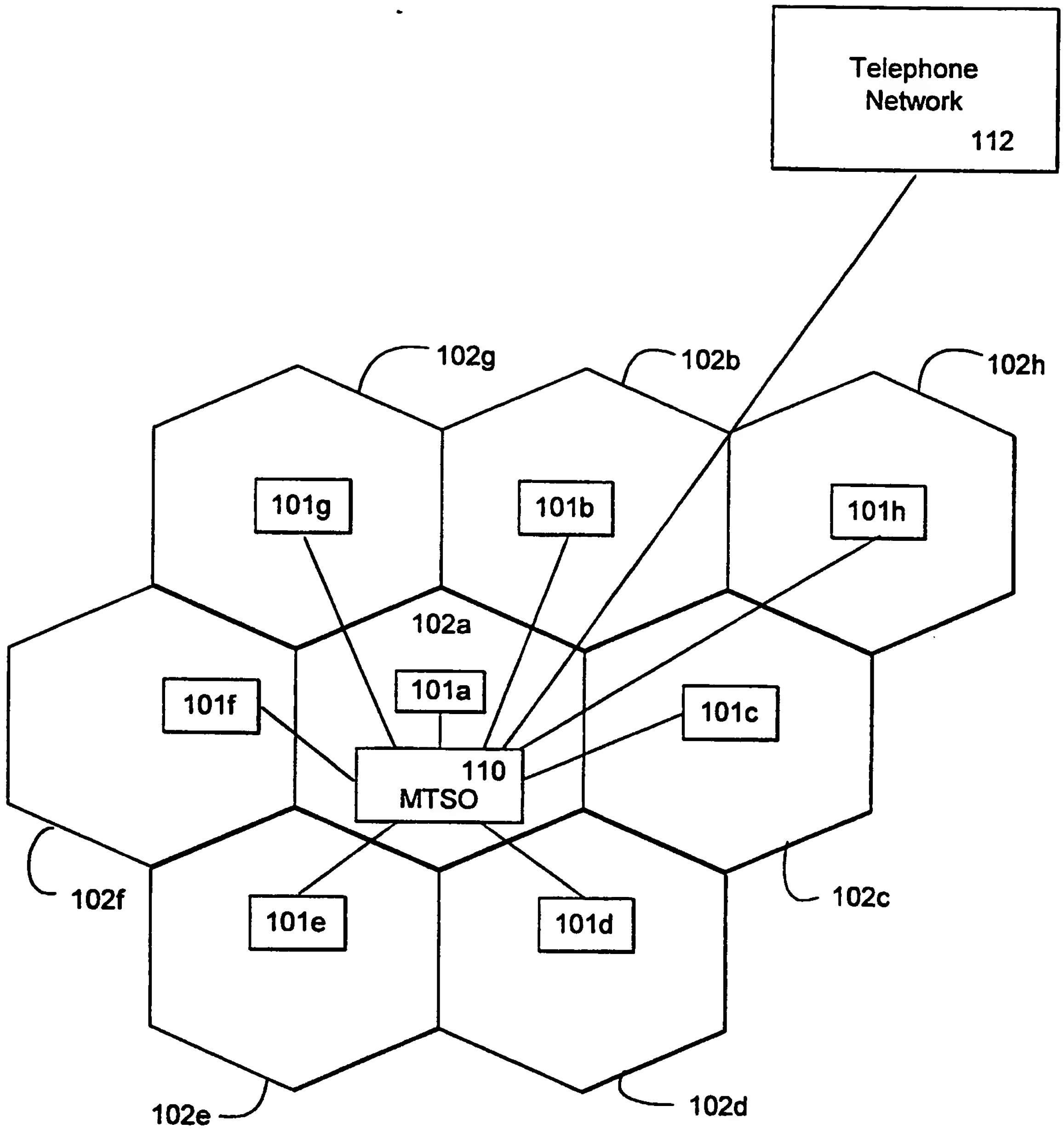

Telephone
Network
112
102g
102b
102h
101g
101b
101h
102a
101f
101a
101c
110
MTSO
102f
101e
101d
102c
102e
102d

FIG. 2

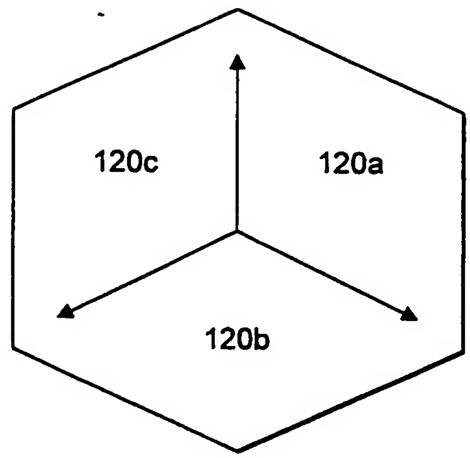


FIG. 3

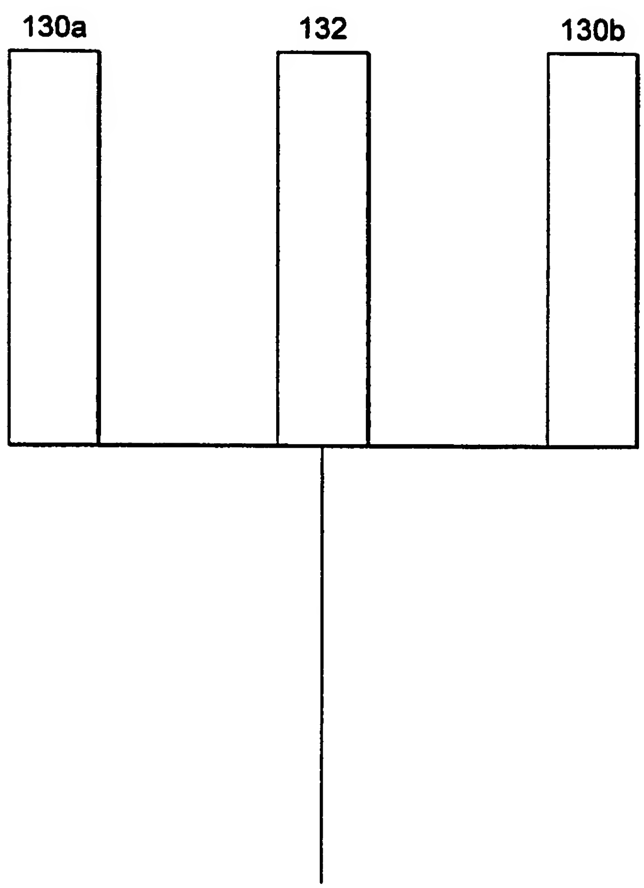


FIG. 4

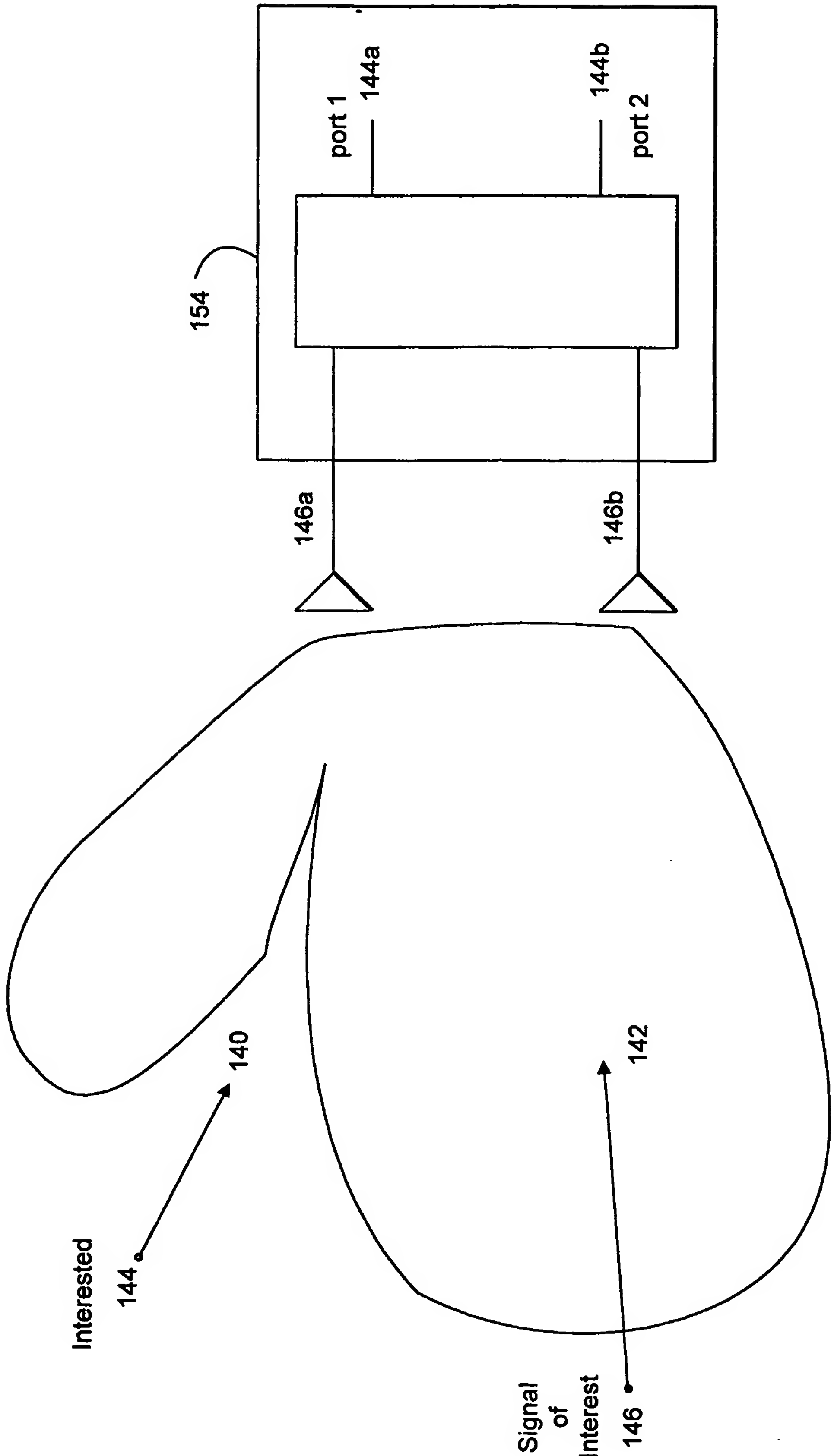

154
port 1
144a
144b
port 2
146a
146b
140
142
Interested
144
Signal
of
Interest
146

FIG. 5

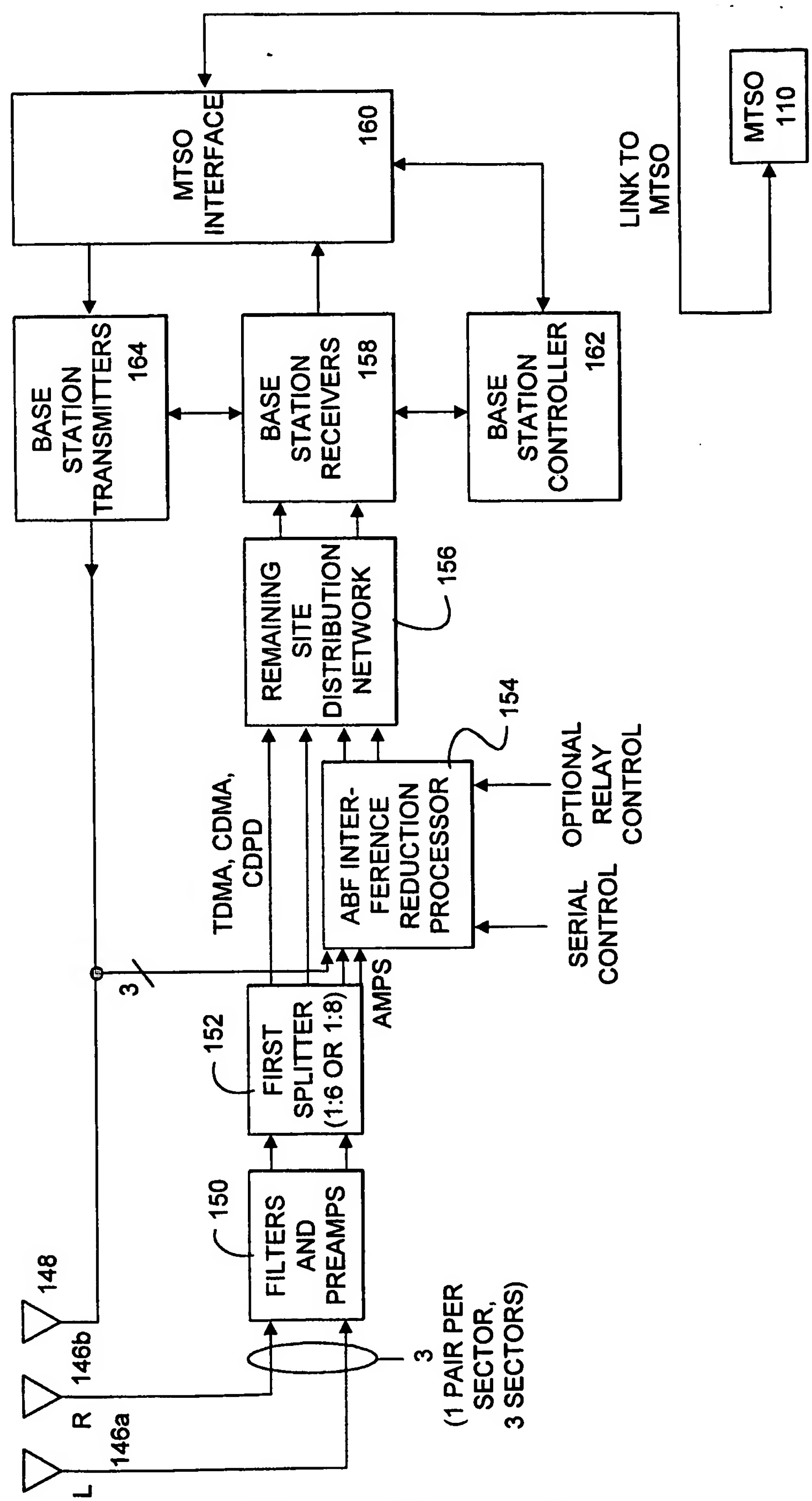
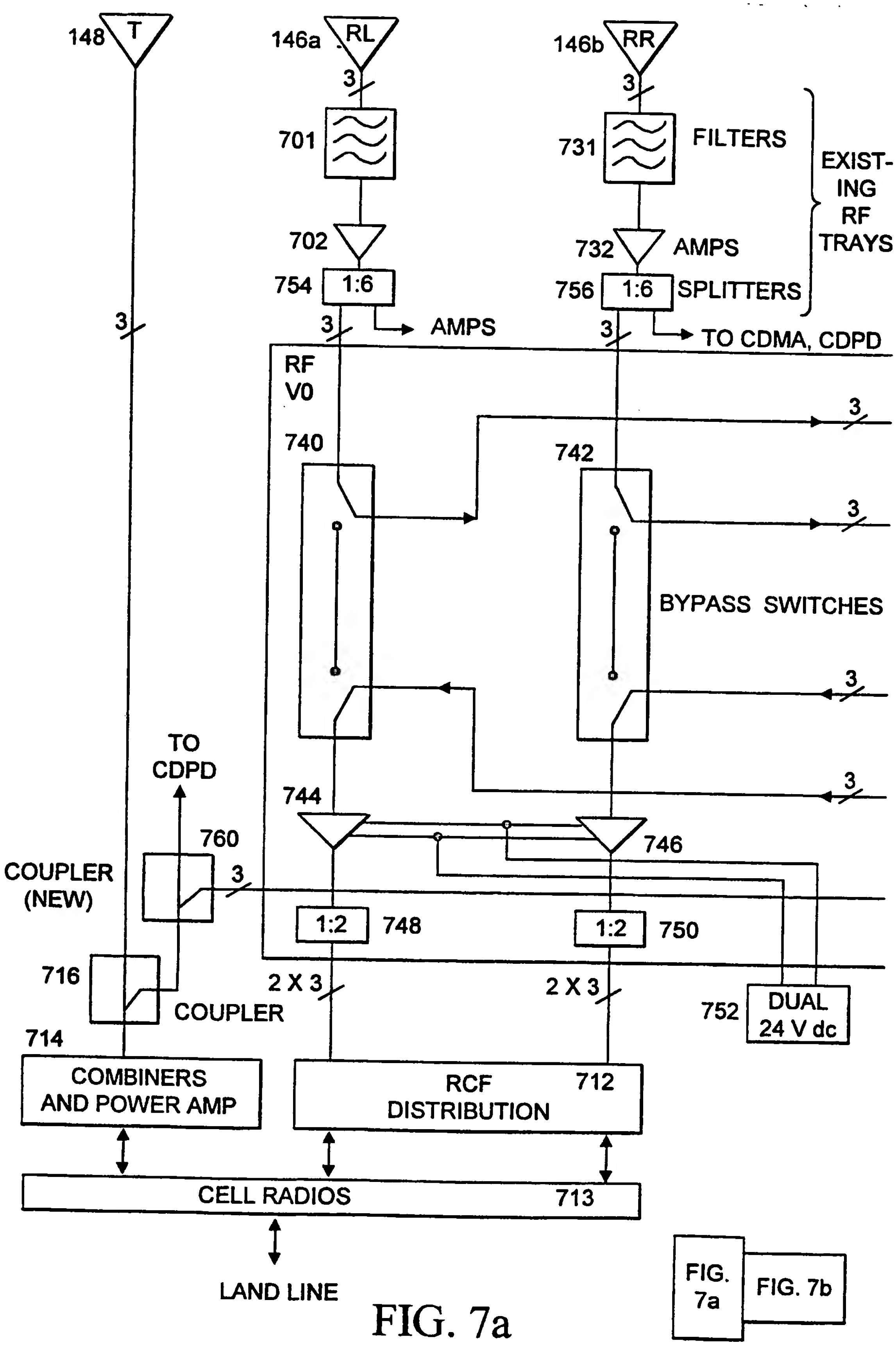

MTSO INTERFACE
160
BASE STATION TRANSMITTERS
164
BASE STATION RECEIVERS
158
BASE STATION CONTROLLER
162
LINK TO MTSO
MTSO
110
REMAINING SITE DISTRIBUTION NETWORK
156
TDMA, CDMA, CDPD
ABF INTER- FERENCE REDUCTION PROCESSOR
154
OPTIONAL RELAY CONTROL
SERIAL CONTROL
3
AMPS
FIRST SPLITTER (1:6 OR 1:8)
152
FILTERS AND PREAMPS
150
148
146b
R
146a
L
3
(1 PAIR PER SECTOR, 3 SECTORS)

FIG. 6



148
T
146a
RL
146b
RR
3
3
701
731
FILTERS
EXIST-
ING
RF
TRAYS
702
732
AMPS
754
1:6
756
1:6
SPLITTERS
3
3
AMPS
3
TO CDMA, CDPD
RF
V0
740
742
3
3
BYPASS SWITCHES
3
3
TO
CDPD
744
760
746
COUPLER
(NEW)
3
1:2
748
1:2
750
716
2 X 3
2 X 3
COUPLER
752
DUAL
24 V dc
714
COMBINERS
AND POWER AMP
RCF
DISTRIBUTION
712
CELL RADIOS
713
LAND LINE
FIG. 7a
FIG. 7b

FIG. 7a

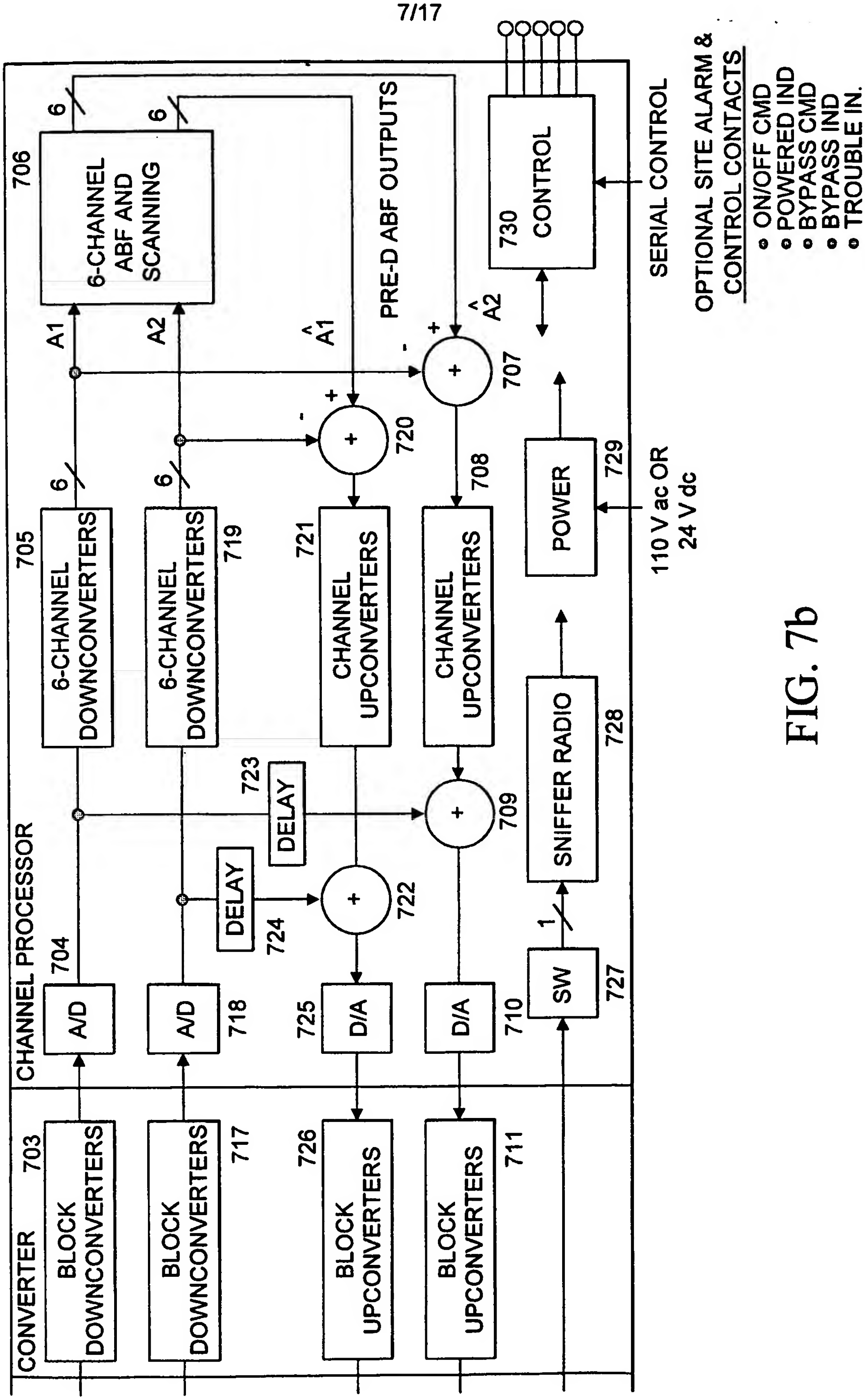

CONVERTER
CHANNEL PROCESSOR
BLOCK DOWNCONVERTERS
703
BLOCK DOWNCONVERTERS
717
BLOCK UPCONVERTERS
726
BLOCK UPCONVERTERS
711
A/D
704
A/D
718
D/A
725
D/A
710
SW
727
1
DELAY
724
DELAY
723
722
709
SNIFFER RADIO
728
6-CHANNEL DOWNCONVERTERS
705
6-CHANNEL DOWNCONVERTERS
719
CHANNEL UPCONVERTERS
721
CHANNEL UPCONVERTERS
708
POWER
729
110 V ac OR 24 V dc
6
720
707
A1
A2
Â1
Â2
6-CHANNEL ABF AND SCANNING
706
PRE-D ABF OUTPUTS
730
CONTROL
SERIAL CONTROL
OPTIONAL SITE ALARM & CONTROL CONTACTS
ON/OFF CMD
POWERED IND
BYPASS CMD
BYPASS IND
TROUBLE IN.

FIG. 7b

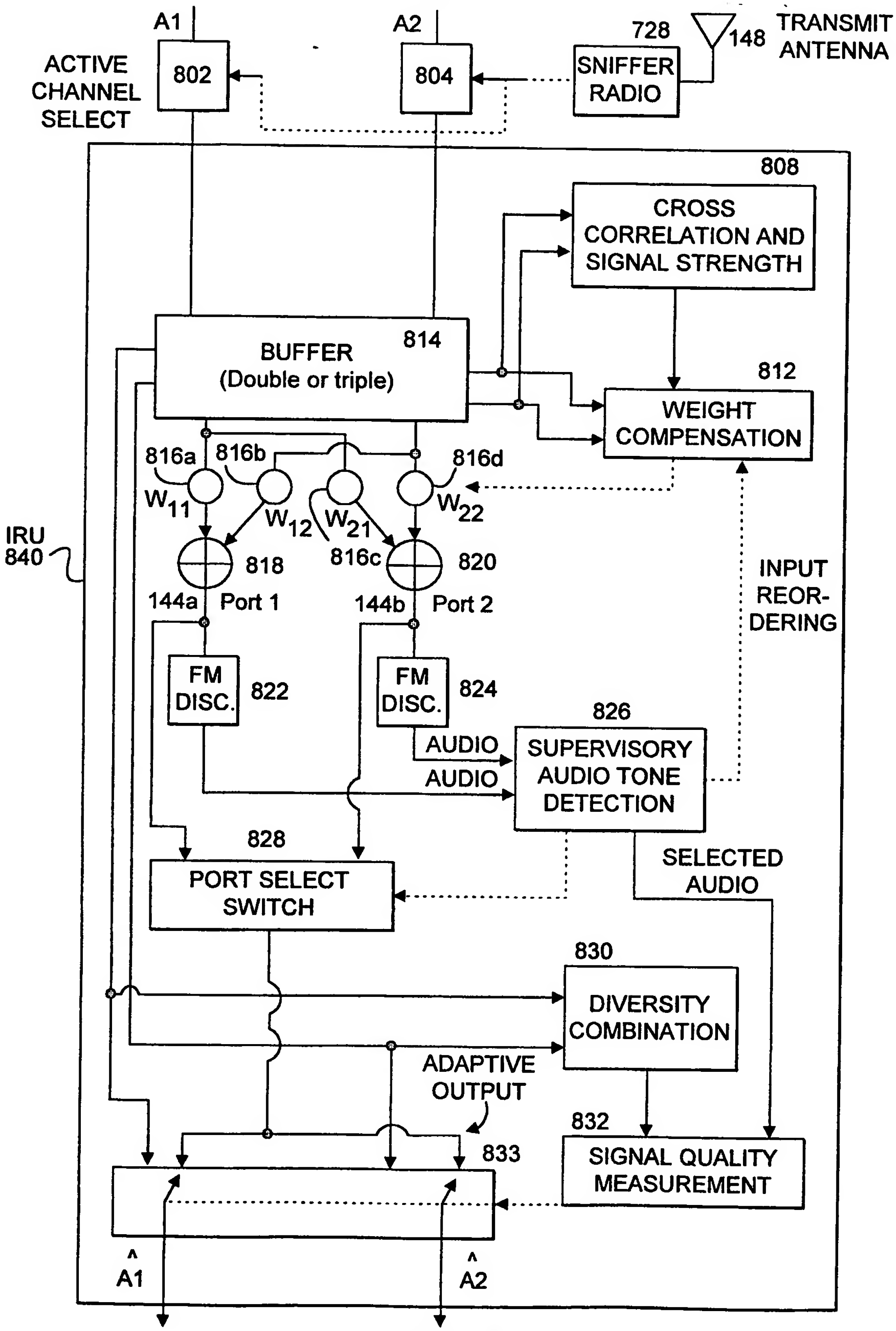

A1
A2
ACTIVE CHANNEL SELECT
802
804
728
SNIFFER RADIO
148
TRANSMIT ANTENNA
808
CROSS CORRELATION AND SIGNAL STRENGTH
BUFFER (Double or triple)
814
812
WEIGHT COMPENSATION
816a
816b
816d
W11
W12
W21
W22
IRU 840
818
816c
820
144a
Port 1
144b
Port 2
INPUT REOR-DERING
FM DISC.
822
FM DISC.
824
826
AUDIO
AUDIO
SUPERVISORY AUDIO TONE DETECTION
828
SELECTED AUDIO
PORT SELECT SWITCH
830
DIVERSITY COMBINATION
ADAPTIVE OUTPUT
832
833
SIGNAL QUALITY MEASUREMENT
Â1
Â2

FIG. 8

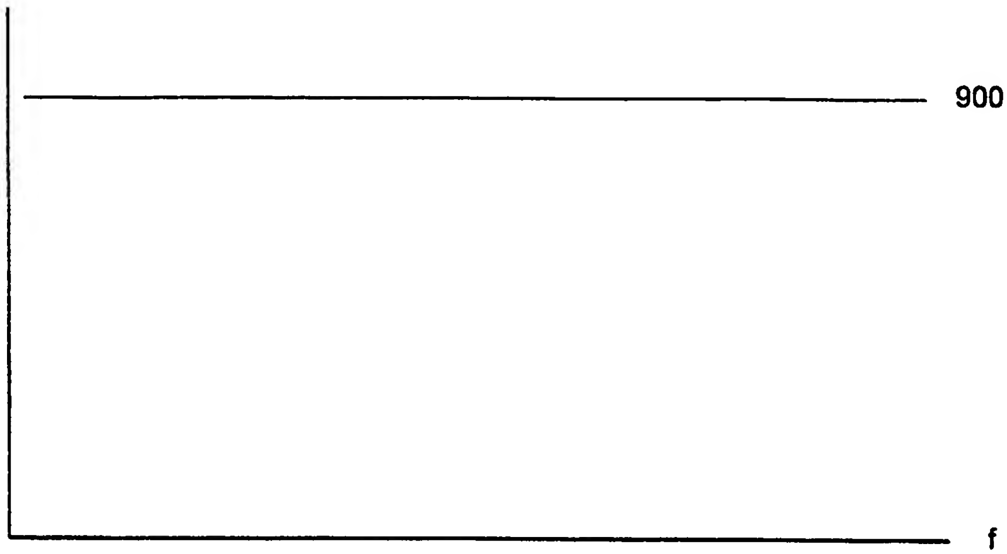


FIG. 9a

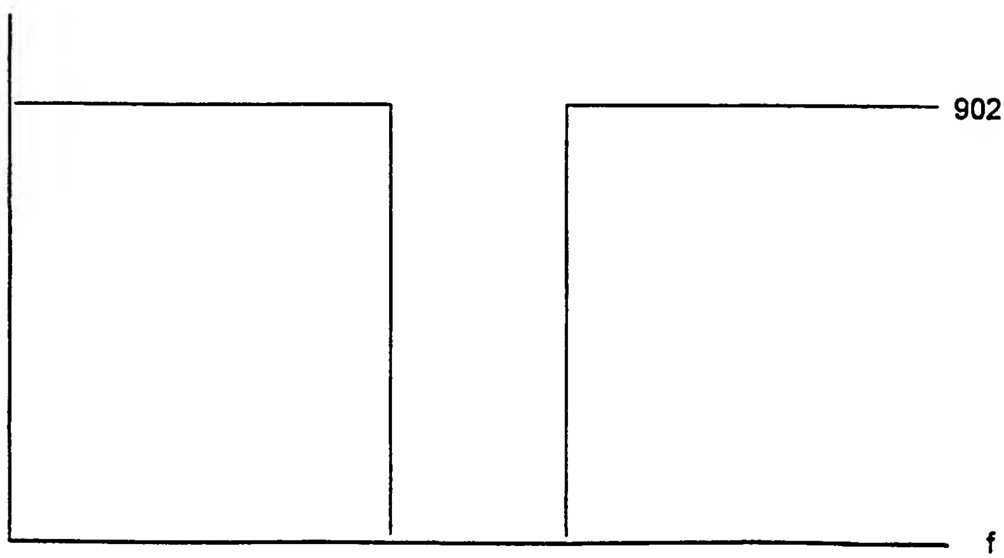


FIG. 9b

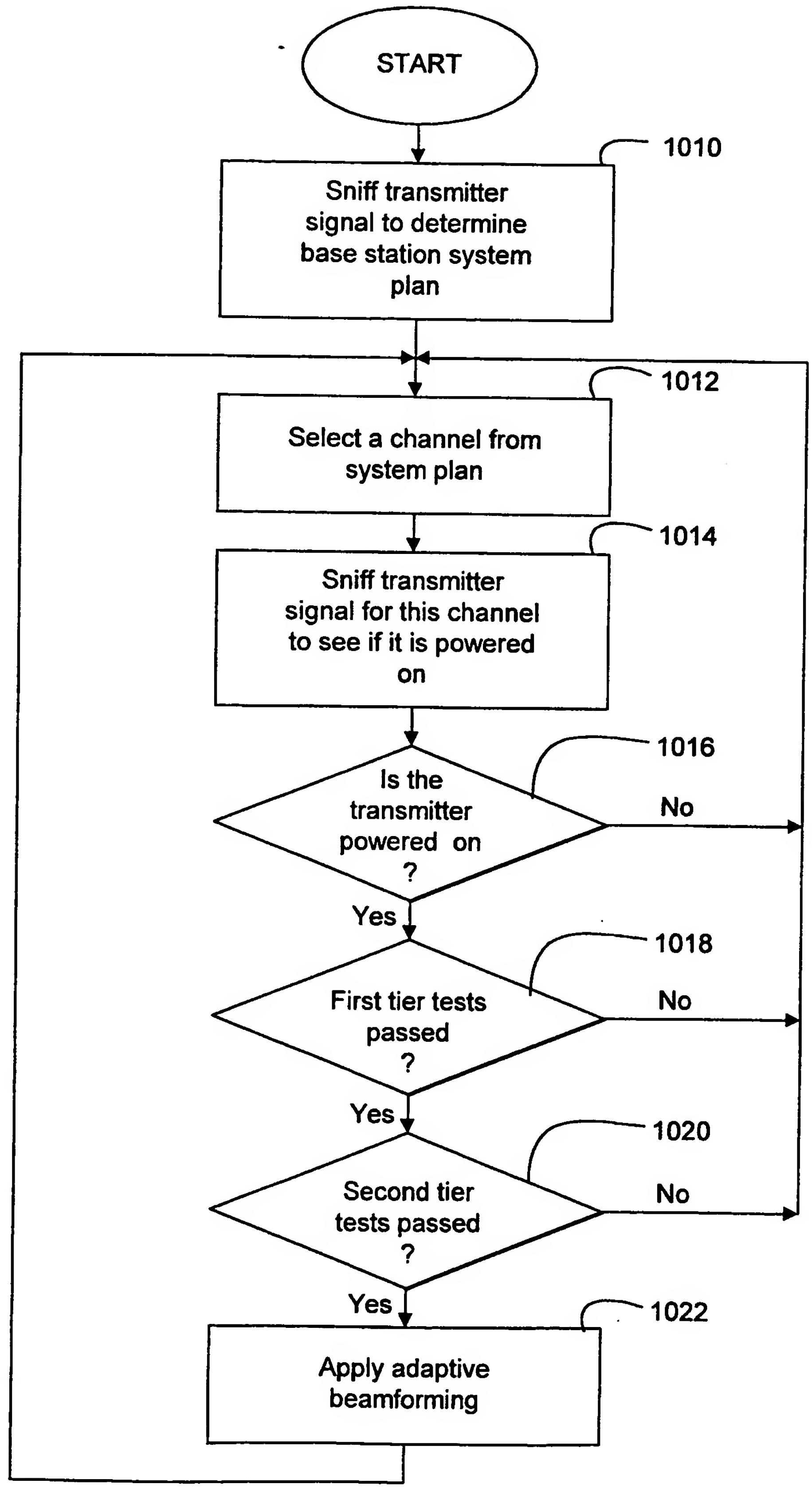

START
1010
Sniff transmitter signal to determine base station system plan
1012
Select a channel from system plan
1014
Sniff transmitter signal for this channel to see if it is powered on
1016
Is the transmitter powered on ?
No
Yes
1018
First tier tests passed ?
No
Yes
1020
Second tier tests passed ?
No
Yes
1022
Apply adaptive beamforming

FIG. 10

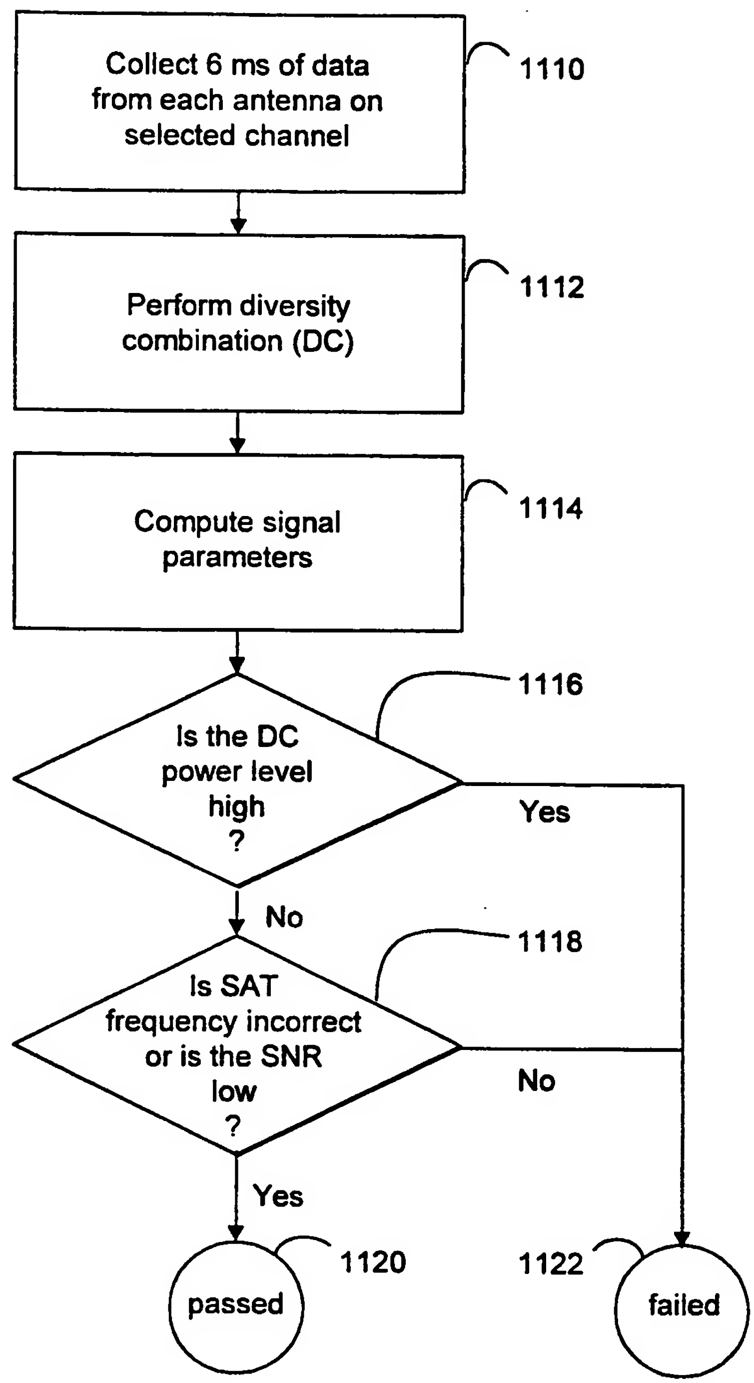

Collect 6 ms of data from each antenna on selected channel
1110
Perform diversity combination (DC)
1112
Compute signal parameters
1114
Is the DC power level high ?
1116
Yes
No
Is SAT frequency incorrect or is the SNR low ?
1118
No
Yes
passed
1120
1122
failed

FIG. 11

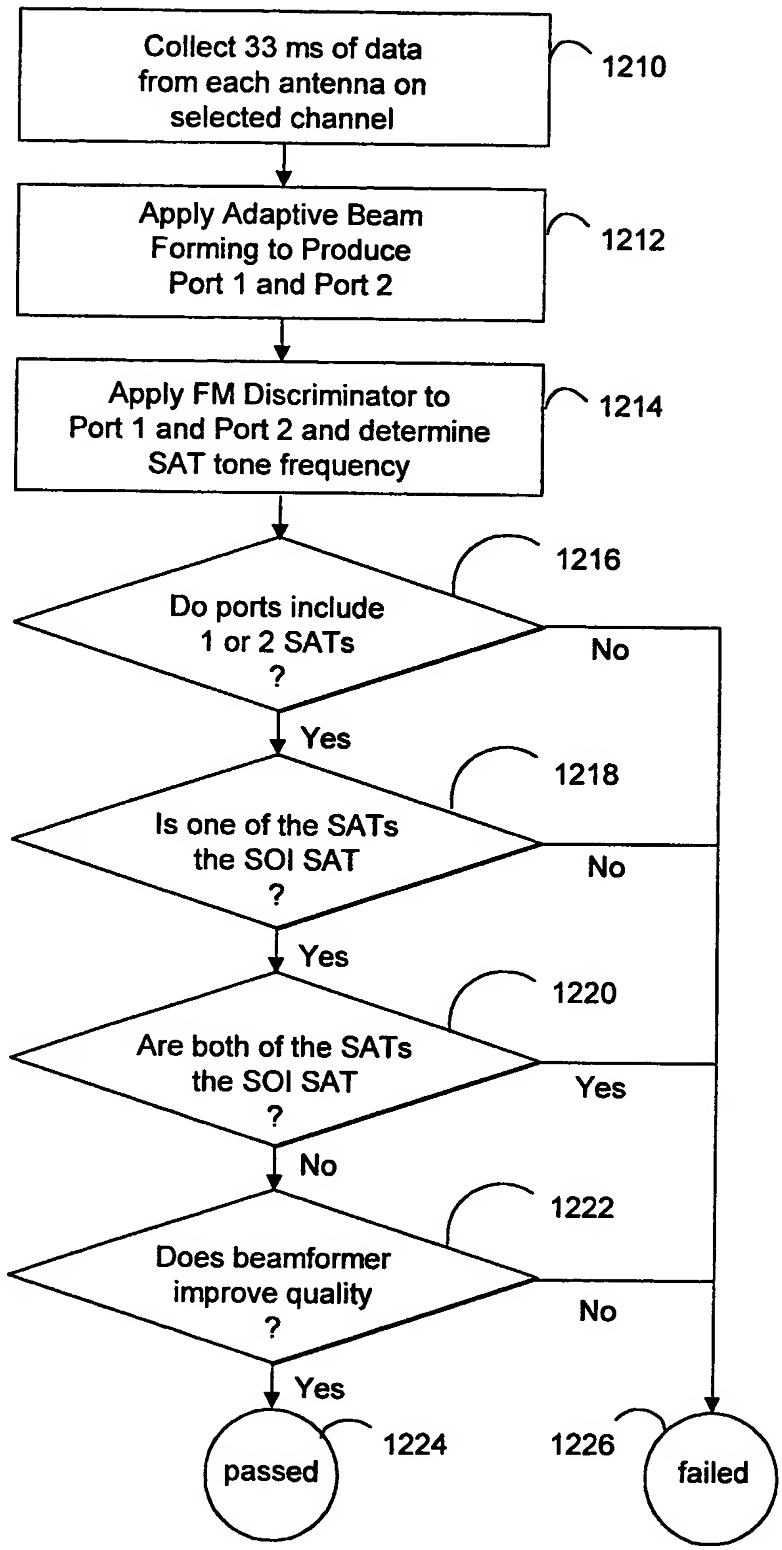

Collect 33 ms of data from each antenna on selected channel
1210
Apply Adaptive Beam Forming to Produce Port 1 and Port 2
1212
Apply FM Discriminator to Port 1 and Port 2 and determine SAT tone frequency
1214
Do ports include 1 or 2 SATs ?
1216
No
Yes
Is one of the SATs the SOI SAT ?
1218
No
Yes
Are both of the SATs the SOI SAT ?
1220
Yes
No
Does beamformer improve quality ?
1222
No
Yes
passed
1224
1226
failed

FIG. 12

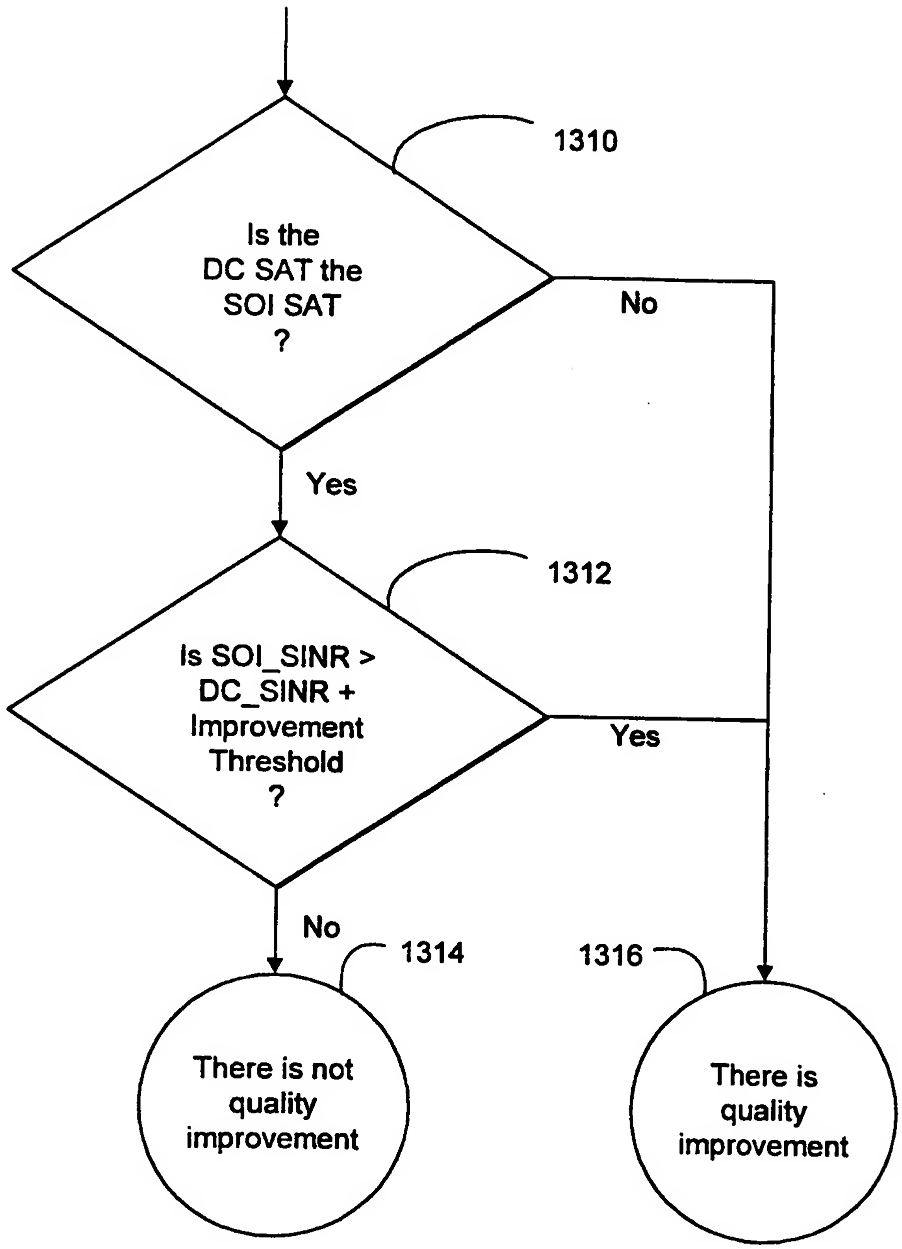

1310
Is the
DC SAT the
SOI SAT
?
No
Yes
1312
Is SOI_SINR >
DC_SINR +
Improvement
Threshold
?
Yes
No
1314
1316
There is not
quality
improvement
There is
quality
improvement

FIG. 13

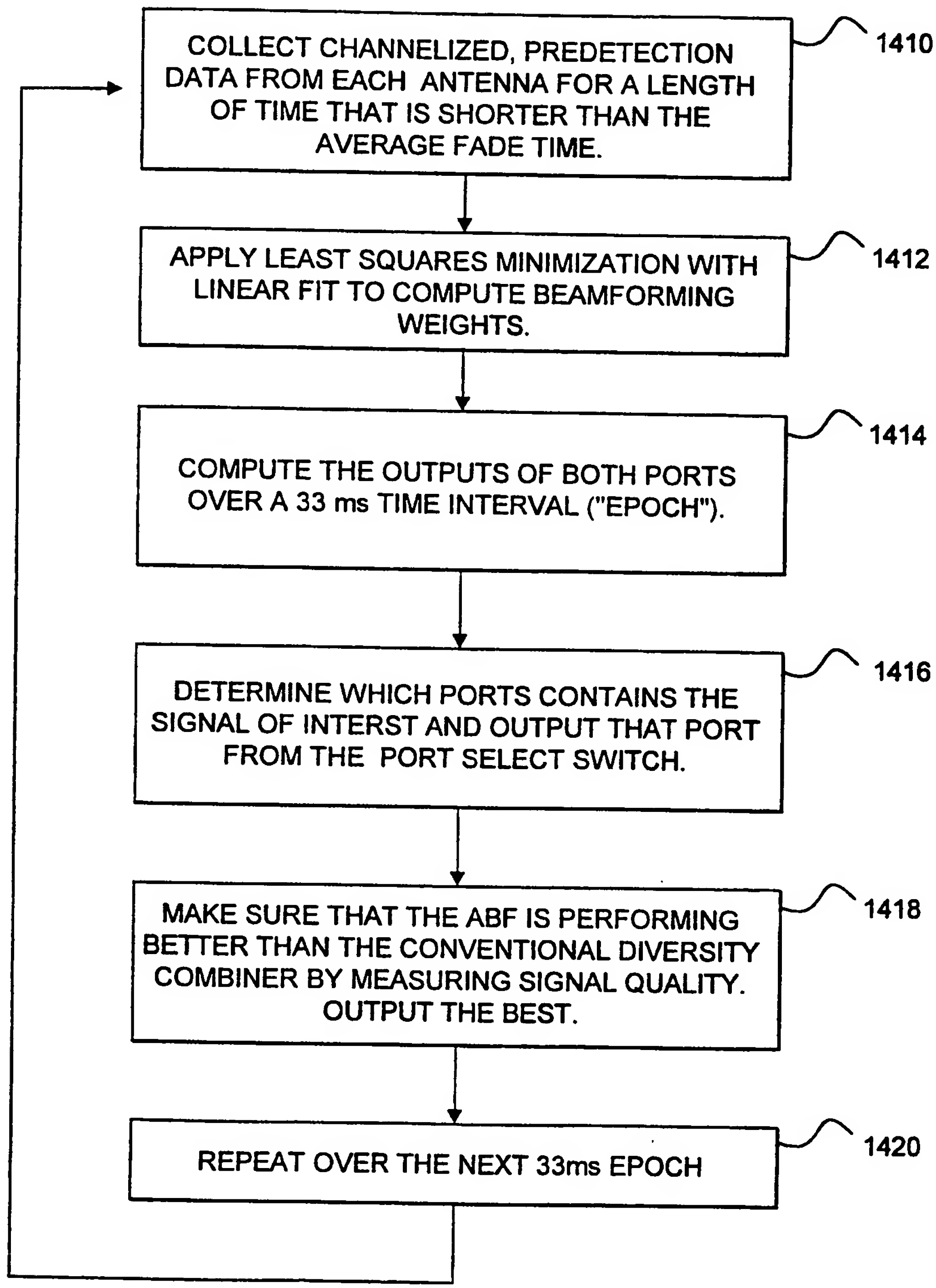

COLLECT CHANNELIZED, PREDETECTION DATA FROM EACH ANTENNA FOR A LENGTH OF TIME THAT IS SHORTER THAN THE AVERAGE FADE TIME.
1410
APPLY LEAST SQUARES MINIMIZATION WITH LINEAR FIT TO COMPUTE BEAMFORMING WEIGHTS.
1412
COMPUTE THE OUTPUTS OF BOTH PORTS OVER A 33 ms TIME INTERVAL ("EPOCH").
1414
DETERMINE WHICH PORTS CONTAINS THE SIGNAL OF INTERST AND OUTPUT THAT PORT FROM THE PORT SELECT SWITCH.
1416
MAKE SURE THAT THE ABF IS PERFORMING BETTER THAN THE CONVENTIONAL DIVERSITY COMBINER BY MEASURING SIGNAL QUALITY. OUTPUT THE BEST.
1418
REPEAT OVER THE NEXT 33ms EPOCH
1420

FIG. 14

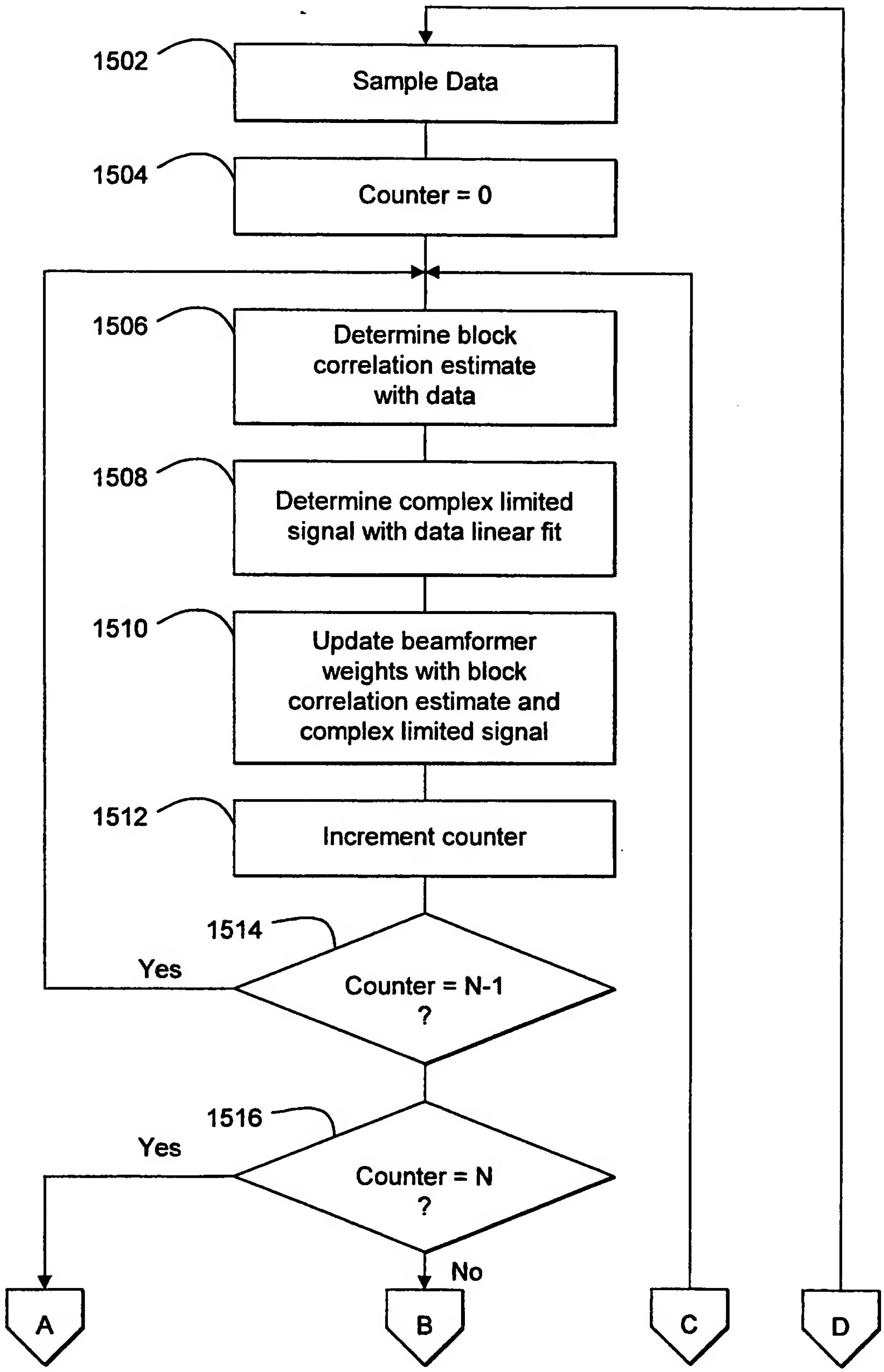

1502
Sample Data
1504
Counter = 0
1506
Determine block correlation estimate with data
1508
Determine complex limited signal with data linear fit
1510
Update beamformer weights with block correlation estimate and complex limited signal
1512
Increment counter
1514
Yes
Counter = N-1 ?
1516
Yes
Counter = N ?
No
A
B
C
D

FIG. 15a

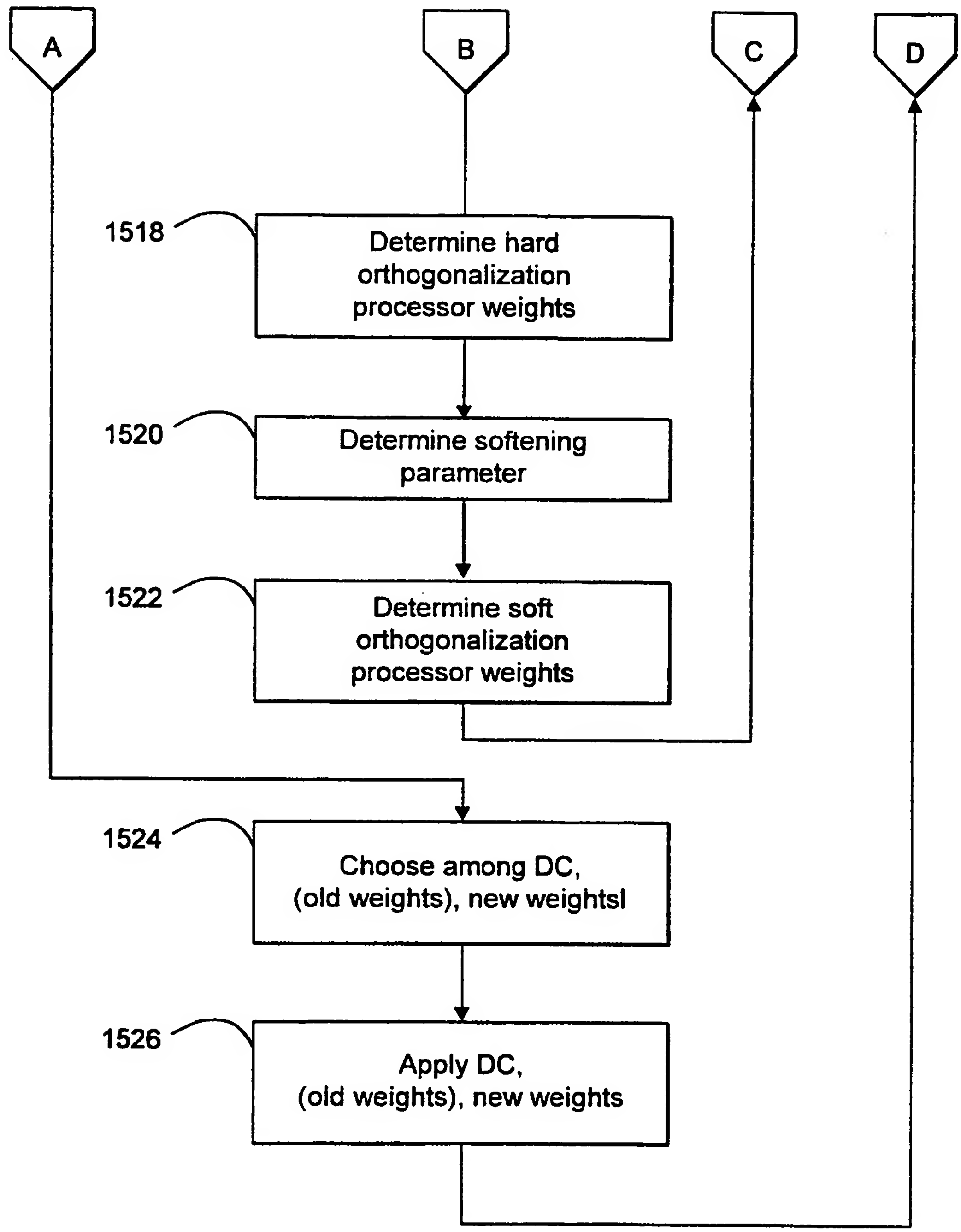

A
B
C
D
1518
Determine hard orthogonalization processor weights
1520
Determine softening parameter
1522
Determine soft orthogonalization processor weights
1524
Choose among DC, (old weights), new weightsl
1526
Apply DC, (old weights), new weights

FIG. 15b

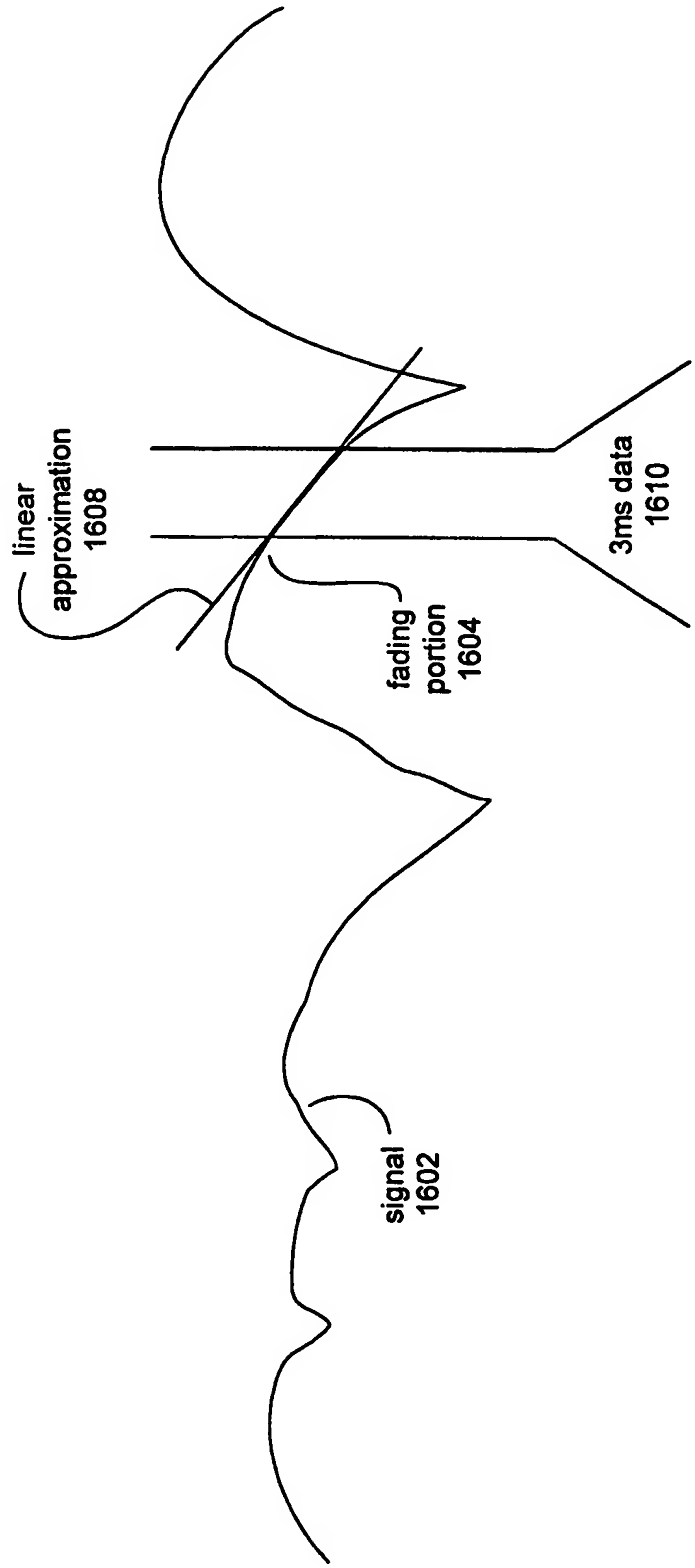

linear approximation 1608
3ms data 1610
fading portion 1604
signal 1602

FIG. 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US97/21025

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :H04Q 07/00
US CL :455/562
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 455/562,561,422,440,450,456,524,62,63,103,132,133,134,135,137,138,13,272,275,276.1,277 .1,278.1,279.1; 342/367,368,374.

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS
search terms: beamforming, beamformer, beamforms, diversity, adaptive, array, antenna, least mean, linear, base station.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y,P ------ X,P	US 5,602,555 A (SEARLE et al) 11 February 1997, see col. 10 lines 47-68.	1-13,30, 39,42,45-48 -------- 20,29,38,
Y,P	US 5,634,199 A (GERLACH) 27 May 1997, see col. 3, lines 52-67.	1-13,30, 39,42,45-48
X,P ----- Y,P	US 5,615,409 A (FORSSEN et al) 25 March 1997, see col. 4, lines 15-35.	37,38 ---- 12,39,47

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
02 APRIL 1998	05 MAY 1998

Name and mailing address of the ISA/US	Authorized officer
Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231	Philip Sobutka
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CORRECTED VERSION*

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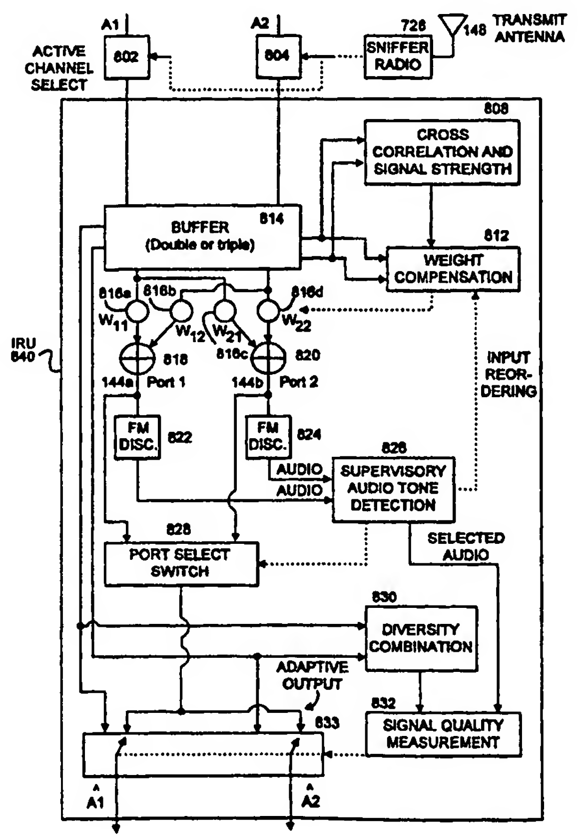
(81) Designated States: AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, CA, CH, CN, CU, CZ, DE, DK, EE, ES, FI, GB, GE, GH, HU, ID, IL, IS, JP, KE, KG, KP, KR, KZ, LK, LR, LS, LT, LU, LV, MD, MG, MK, MN, MW, MX, NO, NZ, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TR, TT, UA, UG, US, UZ, VN, YU, ZW, ARIPO patent (GH, KE, LS, MW, SD, SZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, ML, MR, NE, SN, TD, TG).

Published
With international search report.
Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.

(54) Title: ADAPTIVE BEAMFORMING FOR WIRELESS COMMUNICATION

(57) Abstract

Method and circuitry for interference reduction in wireless communication (840); reducing interference from a source received in the same channel as a signal of interest (142); adaptive beamforming and scanning (154) so as to direct a sensitivity null (145) toward an interfering signal while still receiving the signal of interest; scanning wireless channels and applying adaptive beamforming to channels having interference. Selecting among signals based on a supervisory audio tone (826). Selecting a sample having a duration less than an inverse of a fade rate of the signal; determining a linear fit to a sample and transforming a signal based on minimization of variance from the linear fit.



*(Referred to in PCT Gazette No. 38/1998, Section II)

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